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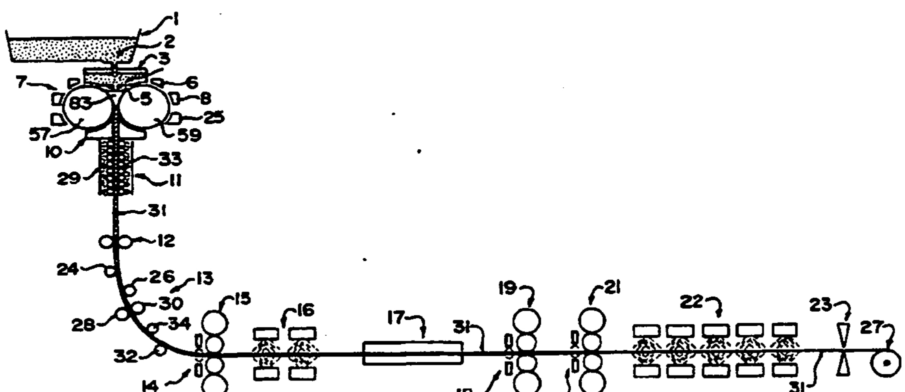

(57) Abstract

Twin-roll casting method for casting steel strand of thickness preferably 5 to 35 mm. Immediately downstream of the twin rolls, the cast strand is cooled by directing it through a stationary cooled mold (10). Subsequent to exiting the stationary mold, the strand is directed through a series of cooling rolls thereby further cooling the strand both by contact with the rolls and by spraying with water. The level of the pool of molten steel above the twin rolls is maintained such that the surface of each twin roll located between the meniscus of the pool of molten steel and the gap between the twin rolls is preferably in the range about 30° to about 45°. The strand is directed through the stationary mold (10) at the rate of 1 to about 6 tonnes per minute. The surfaces of the twin rolls are continually lubricated, ground, and heated. Operational parameters are adjusted so that solidification of the strand occurs less than about 10 % by contact with the twin rolls and at least about 90 % downstream of the gap between the twin rolls. The metallurgical length is selected to be between about 0 and 3 m. The cast strand is subjected to soft reduction for segregation control. Downstream of the stationary mold (10), the cast strand may be reduced in thickness by a series of hard reductions to form steel strip having a thickness of about one-third or less of the thickness of the cast strand.

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METHOD OF CASTING AND ROLLING STEEL USING TWIN-ROLL CASTER

RELATED APPLICATIONS

This application is a counterpart of U.S. Application Serial No. 08/468,009 which is a continuation-in-part of U.S. Patent Application Serial No. 08/272,678.

FIELD OF THE INVENTION

This invention relates to a method for casting and rolling steel using twin-roll casters.

BACKGROUND; PRIOR ART

Conventionally, steel is cast in a continuous casting process by pouring the molten steel from a tundish into a mold having a rectangular cross-section that defines the width and thickness of the steel strand to be cast. The mold is typically water-cooled and is sufficiently long in extension that the outer shell of the steel solidifies sufficiently within the casting mold such that the steel retains its shape and does not burst open (break out). A caster of this sort is typically oscillated in the longitudinal (vertical) direction. Casting powder is applied so that steel will not stick to the inside walls of the casting mold, and so as to minimize radiant heat loss, and to absorb unwanted inclusions.

Downstream of the casting mold are typically arranged a series of supporting rolls for the cast strand which give it support while its core is still partly molten, thereby permitting it to continue to solidify without danger of rupture (break-out). These rolls control the exterior thickness dimension of the solid shell of the casting but typically do not reduce the dimension appreciably. In some cases, these rolls may impart a slight reduction to the

steel casting while its core is still soft or even molten, for the purpose of centerline segregation control (see, e.g., L.K. Chiang, "Application of Soft Reduction Technique for Improving Centerline Segregation in Continuously Cast Slab", 1989 Steelmaking Conference Proceedings 81).

As an alternative to a conventional caster of the foregoing sort for the continuous casting of steel slab, there may be provided for the casting of a relatively thin steel strand, a twin-roll caster. The concept of a twin-roll caster is about a century old; variants of such casters have received attention recently for the casting of very thin steel strand not intended to be further reduced from the as-cast thickness. In a twin-roll caster, a pair of identical horizontally disposed casting rolls of adequately large diameter are aligned to be axially parallel to one another, and are rotatably mounted with a slight gap between the two rolls. The width of the gap is approximately equal to the thickness of the casting to be made. The rolls rotate in opposite senses downwardly toward the narrowest part of the gap, referred to as the "kissing point". Viewed end on, the left roll rotates clockwise and the right roll counterclockwise. Molten steel is supplied from a tundish above the rolls to form a pool just above the gap between the two rolls. The molten steel solidifies as it passes towards and through the gap between the two rolls, and exits as a strand having a solid shell whose thickness is predetermined by the gap between the two casting rolls.

Such twin-roll casters are illustrated and described, for example, in Japanese published patent specification 62-77151 dated 9 April 1987, Japanese published patent specification 1-249246 dated 4 October 1989, and Japanese published patent specification 3-90261 dated 16 April 1991.

Conventionally, prior twin-roll casters have included support rolls immediately downstream of the twin casting rolls that give support to the cast strand as it leaves the twin casting rolls, and that redirect the cast strand from vertical orientation to horizontal orientation. Redirection rolls of this type are commonplace in steel making; representative such rolls are illustrated, for example, in various of the above-mentioned published Japanese specifications and are also used apart from twin-roll casters: see, *e.g.* Scholz U.S. patent 5,065,811 dated 19 November 1991.

Conventionally, in twin-roll casters such as the foregoing, only the twin casting rolls themselves constitute the means for defining the dimensions and particularly the thickness of the cast strand, and constitute the only means for cooling the molten steel sufficiently that it is sufficiently solid to avoid break-outs. However, this conventional arrangement permits the molten steel to be cooled only over a relatively short arcuate segment (typically of the order of 45°) of the periphery of the twin casting rolls with which the solidifying steel comes into contact. Conventionally, downstream of the twin casting rolls, no further special cooling arrangement is provided; consequently, downstream cooling is less rapid than cooling imparted by the twin casting rolls. Furthermore, the cast strand must be solid as it leaves the twin casting rolls, and this means that the cooling imparted by the twin casting rolls is critical. Obviously, the greater the speed of longitudinal travel of the cast steel strand, the more acute the foregoing problem. This limited contact of the cast strand with the available cooling surface of the twin casting rolls can, if higher casting speeds or the casting of thicker strand is attempted, lead to thinner shells, and to attendant increased risk of break-outs.

Furthermore, the absence in conventional apparatus and processes of downstream hard reduction implies the absence of preferred dimensional, surface and metallurgical quality of the coiled strip produced from such castings. In a conventional twin-roll caster, the upper limit on the gap between the twin casting rolls that determines the thickness of the cast strand is relatively small - typically of the order of about 1 to 5 mm. If the gap is made larger, the steel strand tends not to retain its shape, and break-outs can occur.

The advantage of conventional twin-roll casters has always appeared to be that they could cast steel of a dimension that is very small compared to the dimensions of conventional castings that are prepared using an oscillating mold of relatively large rectangular open area. Casting the steel in a thinner dimension using twin-roll casters has the advantage for some grades of steel of eliminating or minimizing the need for reduction rolling downstream of the caster, albeit with some loss of surface finish and less than optimum metallurgical quality, but with the benefit that much lower capital is required to build a steel-making facility than would be required for a conventional slab-casting and rolling mill.

It can be seen that drawbacks associated with conventional twin-roll casting include the following:

(i) Relatively low productivity, because the casting throughput is limited by the requirement that the strand be completely solid or almost so from the kissing point of the twin rolls onward. Annual production capacity of the order of a half-million tonnes is obtainable, but not much more.

(ii) Relatively low casting speed for thicker steel strand, again because of the need for solidification at the kissing point of the twin rolls. At higher speeds, the casting is not completely solid and break-outs can occur.

Bulging of the strand is also increasingly a problem as higher casting speeds are attempted.

(iii) A range of thicknesses of the cast strand insufficient to permit optimum downstream hot rolling reduction. This limitation implies that the dimensional, profile, surface and metallurgical quality of conventional twin-roll cast steel is inadequate to meet more demanding customer specifications.

SUMMARY OF THE INVENTION

My invention has both apparatus and method aspects. This application is directed to the method aspects. The apparatus aspects are described and claimed more fully in the following U.S. patent applications:

Number	Date

I have discovered that twin-roll casting may be used to produce cast strand of a greater thickness range than is normal for twin-roll casters. A cast strand according to my invention may have extended metallurgical length that will allow the solidification of the strand to be continued beyond the twin-roll caster exit such that the strand retains its shape without break-out. Twin-roll casting according to my invention may be used in combination with suitable downstream reduction using an in-line hot rolling process. My method can produce a finished product of superior quality relative to the product conventionally produced by twin-roll casting.

To achieve the foregoing objectives, according to one aspect of my invention, a pool of molten steel is formed and maintained above the gap between substantially identical twin rolls of a twin-roll caster. The rolls are rotated at substantially identical speeds in opposite senses downwardly toward the gap above which the pool of molten steel lies. The cast strand is directed into and through the mouth of a stationary mold located immediately adjacent, underneath and downstream of the twin rolls, said mouth being of a width substantially identical to the thickness of the cast strand. The cast strand is cooled as it passes through the gap between the opposed segments of the stationary mold. The strand is further processed downstream of the stationary mold to form a steel strip product.

Cooling of the cast strand is enhanced by passing a flow of cooling water through the interior of the twin rolls and of the stationary mold.

By directing the cast strand immediately through a stationary mold so that the strand continues to cool and solidify after leaving the twin-rolls, the strand may be successfully cast in a wider range of thicknesses than is conventionally used in twin-roll casting, allowing subsequent reduction rolling to be used. All that the twin rolls need do is to form a solid thin skin to delimit the dimensions of the cast strand; the solidification of the large majority of the mass of the cast strand should occur downstream of the twin rolls.

In preferred variants of the method of my invention, I provide further additional features, as follows:

The thickness of the cast strand as determined by the gap between the twin casting rolls may be selected to be

as wide as 50 mm or as narrow as 3 mm, but is preferably selected within the range of about 5 mm to about 35 mm. By permitting a thicker cast strand than that possible in conventional twin-roll casting, downstream hot rolling reduction becomes possible.

Subsequent to exiting the stationary mold, the strand is directed through a series of cooling rolls thereby further cooling the strand as it passes between the cooling rolls prior to hard reduction rolling of the strand. Such processing may additionally comprise spraying the cast strand with water as it passes between the cooling rolls.

The side of the strand may also be sprayed with water as it passes through the gap between the segments of the stationary mold.

The level of the pool of molten steel is maintained such that the surface of each twin roll located between the meniscus of the pool of molten steel and the gap between the twin rolls is in the range about 25° to about 50°. Preferably, the range should be about 30° to about 45°.

The strand is directed through the stationary mold at the rate of about 1 to about 6 tonnes per minute.

A lubricant is applied to the surfaces of the twin rolls before those surfaces enter the pool of molten steel above the gap between the twin rolls. The lubricant may be a selected vegetable oil, for example, rapeseed oil. Such lubricant tends to prevent sticker type break-outs of the cast strand. The use of such lubricant is especially desirable when casting thicker strands at a high casting speed, and may be essential if, as preferred, no casting powder is used.

The surfaces of the twin rolls are ground continually thereby to maintain a desired profile and smoothness of the roll surfaces.

Heat is applied to the surfaces of the twin rolls to raise the surface temperature thereof just prior to those surfaces moving into contact with the pool of molten steel above the gap between the twin rolls thereby to prevent or inhibit distortion of the roll surfaces due to sudden thermal expansion when they come into contact with the pool of molten steel.

Operational parameters (such as rotating and stationary mold temperatures and heat transfer characteristics, casting speed, strand dimensions, water temperatures and flow rates, etc.) are adjusted so that solidification of the strand occurs less than about 10% by contact with the twin rolls and at least about 90% downstream of the gap between the twin rolls.

The metallurgical length is selected to be between about 0 and 3 m.

The cast strand is subjected to soft reduction for segregation control.

According to a further aspect of my invention, downstream of the stationary mold, I propose reducing the cast strand thickness by a series of hard reductions to form steel strip having a thickness of about one-third or less the thickness of the cast strand.

In a preferred embodiment of the further aspect of my invention, I provide the further additional features, as follows:

The cast strand is reduced in a roughing mill and then the intermediate steel strip product is further reduced at the exit of the roughing mill in two successive finishing reductions. The roughing reduction may preferably be of the order of 30% to 50%. Preferably, the intermediate strip product may be additionally cooled by a method such as laminar flow cooling after it exits the roughing mill to a temperature below the Ar_1 and then reheated before the first finishing reduction to a temperature above the Ar_3, at which recrystallization occurs. Preferably, the strip is additionally cooled after the second finishing reduction using a method such as laminar flow cooling. The foregoing controlled processing facilitates the obtention of a preferred smaller grain size when the intermediate strip is then subsequently reduced by at least two further passes through in-line reduction stages. The resulting steel product has preferred metallurgical properties as a consequence of the foregoing processing.

SUMMARY OF THE DRAWINGS

Figure 1 is a schematic elevation view, partly in section, of a preferred embodiment of the twin-roll caster, tundish arrangement and downstream rolling line embodying aspects of the present invention.

Figure 2 is a schematic layout diagram essentially identical to Figure 1, presenting a representative spacing of the sequence of constituent elements of the caster and roll line assembly, expressed in millimetres.

Figure 3 is a schematic end elevation view, partly in section, of a preferred embodiment of the primary and secondary tundishes, twin rolls and stationary mold of the cast arranged in accordance with the principles of the present invention.

Figure 4 is a schematic detailed isometric view of the elements of Figure 3 shown in preferred conjunction in accordance with the principles of the invention.

Figure 5A is a graph illustrating the thickness of cast steel strand, manufactured in accordance with the principles of the present invention, of initially cast thickness 35 mm, showing the thickness as cast and following successive reductions as a plot of downstream distance from the top of the twin-roll caster.

Figure 5B is a graph showing the speed of travel vs. downstream distance characteristic of cast steel strand manufactured in accordance with the principles of the present invention, as cast, and following successive reductions, for an as-cast strand thickness of 35 mm, beginning from the top of the caster.

Figure 5C is a graph plotting the surface temperature, average temperature and centre-line temperature of cast steel strand of initially cast thickness 35 mm, manufactured in accordance with the principles of the present invention, varying as downstream distance from the top of the twin-roll caster through successive stages of the processing sequence according to the present invention.

Figure 6A is a graph illustrating the thickness of cast steel strand, manufactured in accordance with the principles of the present invention, of initially cast thickness 10 mm, showing the thickness as cast and following successive reductions as a plot of downstream distance from the top of the twin-roll caster.

Figure 6B is a graph showing the speed of travel vs. downstream distance characteristic of cast steel strand manufactured in accordance with the principles of the

present invention, as cast, and following successive reductions, for an as-cast strand thickness of 10 mm, beginning from the top of the caster.

Figure 6C is a graph plotting the surface temperature, average temperature and centre-line temperature of cast steel strand of initially cast thickness 10 mm, manufactured in accordance with the principles of the present invention, varying as downstream distance from the top of the twin-roll caster through successive stages of the processing sequence according to the present invention.

Figure 7A is a graph illustrating the thickness of cast steel strand, manufactured in accordance with the principles of the present invention, of initially cast thickness 5 mm, showing the thickness as cast and following successive reductions as a plot of downstream distance from the top of the twin-roll caster.

Figure 7B is a graph showing the speed of travel vs. downstream distance characteristic of cast steel strand manufactured in accordance with the principles of the present invention, as cast, and following successive reductions, for an as-cast strand thickness of 5 mm, beginning from the top of the caster.

Figure 7C is a graph plotting the surface temperature, average temperature and centre-line temperature of cast steel strand of initially cast thickness 5 mm, manufactured in accordance with the principles of the present invention, varying as downstream distance from the top of the twin-roll caster through successive stages of the processing sequence according to the present invention.

DETAILED DESCRIPTION WITH REFERENCE TO THE DRAWINGS

Molten steel is supplied from a primary tundish 1 to a secondary tundish 3 and thence via a guiding shroud 4 to form a pool of molten steel 53 just above the gap 55 formed between a pair of parallel horizontally aligned casting rolls 57, 59 rotating in opposite senses, the roll 57 rotating clockwise, and the roll 59 counterclockwise, as seen in the drawings. Framework, bearings, mountings, etc. are omitted from the drawings for the purposes of clarity and simplicity.

The casting rolls 57 and 59 of the twin-roll caster, referred to generally by reference numeral 7, have copper peripheral cylindrical surfaces. Such twin-roll casters are well-known in the industry; a useful review can be found in the paper by Kasama *et al.*, "Twin Drum Casting Process for Stainless Steel Strand", Proceedings of SNRC-90 Conference, 14-19 October 1990, Pohang, Korea, held by The Korean Institute of Metals and The Institute of Metals, UK, at pp. 643-652. See also Cramb, "New Steel Casting Process for Thin Slab and Strand: A Historical Perspective", Iron and Steelmaker Vol. 20 No. 7, 1988, pp. 45-68. Such twin-roll casters preferably have slightly concave crown profiles in conformity with preferred practice so as to give the cast strand a slight convex profile (positive strand crown profile). The convex profile is desirable for uniform deformation of the hot strand during subsequent hot rolling reduction (see, e.g. Chiang, "Development and Application of Pass Design Models at IPSCO's Steckel Hot Strand Mill" (1992), 33rd MWSP Conference Proceedings, ISS-AIME, Vol. 29. The rolls 57, 59 may be kept within profile specifications by on-line peripheral roll grinders 8 of conventional design.

As the surfaces of rolls 57, 59 rotate into contact with the pool 53 of molten steel, they become hotter. A sudden change in roll surface temperature could distort the roll surface, causing unacceptable surface variation of the cast strand 31. To prevent or mitigate such distortion, hot-air heater 25 located adjacent the rolls 57, 59 blow hot air on the roll surfaces just before these surfaces reach the pool 53 of molten steel, raising the surface temperature of the rolls.

The twin-roll caster 7 casts a strand 31 ranging from about 5 mm to about 35 mm in thickness, or, less economically, sized outside these preferred dimensions to a lower limit of about 3 mm and an upper limit of about 40-50 mm. The casting 31 may preferably be about 900 to about 1800 mm in width, or somewhat outside these dimensions. This as-cast strand 31 is subsequently processed by in-line hot rolling stands (to be described below) to achieve finished strand thickness ranging from about 1.5 mm to about 12 mm, assuming the conventional 3-to-1 reduction of the initial casting. The speed of rotation of the casting rolls 57, 59 is selected to range from about 1.5 rpm to about 12 rpm, the latter for castings of about 5 mm thickness and the former for castings of about 35 mm thickness. Cooling water flow through the rolls 57, 59 is set at about 500 GPM to 1000 GPM per roll to provide optimum cooling effect for good strand surface quality, and is adjusted according to the thickness of the casting.

Within the primary tundish 1 is a continuing supply of molten steel 61 (of, say, 30 tons within tundish 1) replenished on a steady basis from a ladle of molten steel (not shown). Although not shown in the drawings, the primary tundish 1 is preferably equipped with suitable flow control devices, which may, for example, consist of a turbulence inhibitor at the charging area, a baffle and dam,

means for providing argon injection, and a vortex killer at the discharge area to help promote flotation and separation of inclusions for improving steel cleanliness. These devices are all described in my paper "Water Modelling of IPSCO's Slab Caster Tundish" published at page 437 ff. of the 1992 Steelmaking Conference Proceedings.

A stopper rod or slide gate of conventional design (not shown), e.g. the 13QC model sold by Stopinc AG, regulates the liquid steel flow from the primary tundish 1 to a secondary tundish 3. The molten steel flows from the primary tundish 1 to the secondary tundish 3 via a well exit port and associated submerged entry nozzle 2. At the joint between the primary tundish exit port and the submerged entry nozzle 2, an inert atmosphere (argon shield) is provided by means of the argon injection device 48 of conventional design. Such injection devices are used to displace any ambient air (and particularly oxygen) at the joint. The submerged entry nozzle 2 of conventional design, preferably made of high-temperature-resistant refractory material such as high-alumina graphite, shrouds the steel flow from the primary tundish 1 to the secondary tundish 3 to reduce re-oxidation of the molten steel.

A pool 63 of molten steel within the secondary tundish 3 is continuously replenished from the primary tundish 1. The secondary tundish 3 may have, say, a capacity of five tons. The secondary tundish 3 is preferably equipped with a tundish plasma heater (not shown) of conventional design (e.g. of the type supplied by Plasma Energy Corp. and installed in the Nucor Steel plant in Norfolk, Nebraska) to improve temperature control within the range of about 5°C of target superheat temperature during sequence casting operations. For gentle stirring of the steel in the secondary tundish 3, either conventional argon stirring by means of argon injected into the well exit port

51 of the secondary tundish 3 is provided, or else induction stirring devices of the conventional type such as the EMS stirrers supplied by ABB Metallurgy may be used to generate gentle stirring of the molten steel, and to enhance the floating out of the steel of unwanted inclusions.

A guiding shroud 4 of rectangular cross-section fixed to the underside of the secondary tundish 3 and communicating with the exit port 51 of the secondary tundish 3 guides the flow of steel into the pool of molten steel 53 formed immediately above the gap 55 between twin casting rolls 57 and 59. The transverse area dimension of the guiding shroud 4 at the exit port 51 from the secondary tundish 3 is preferably about 5 mm by about 600 mm, which enables the pouring of approximately four tons per minute of liquid steel from the secondary tundish 3 into the pool 53. The guiding shroud 4 tends to isolate the incoming steel from ambient oxygen. Inert gas or a reducing gas or a combination of both is preferably injected above the pool 53 to prevent oxygen from gaining access to the surface of the molten steel pool 53.

Alternative guiding shroud structures suitable for use in the apparatus are described in detail in my copending U.S. patent application Serial No. , filed on .

An anti-splash cover or splash guard 5 is attached to the underside of the secondary tundish 3 and extends as two divided plates generally horizontally outwardly from and spaced by a short distance from the guiding shroud 4. the splash guard 5 is designed to prevent splashed metal droplets from sticking to either of the rotating twin rolls 57, 59. Such spray of droplets is often caused by the impact of the liquid steel stream on the surface of the liquid pool underneath. Another purpose of the splash guard 5 is to minimize radiation heat loss, since, in contrast to

conventional designs, the liquid pool 53 is not covered by casting powder. Nor is the pool 53 in contact with a pouring nozzle or shroud. Therefore, interactions with the atmosphere, slag, and refractories can be significantly reduced, leading to improved cleanliness of the steel.

A preferred splash guard is described in more detail in my copending U.S. patent application Serial No. , filed on .

Mixed gases comprised of about 94% to 98% argon, 1% to 3% CH_4, and 1% to 3% CO_2 supplied at a total pressure slightly above one atmosphere are constantly injected into the space between the splash guard 5 and the liquid steel bath 53 during the casting operation. These gases enter the space above the pool 53 via suitable injector nozzles (not shown). They are prevented from rapidly leaving this space by the close spacing of the bent edges of the splash guard 5 to the peripheries of rolls 57, 59.

The CH_4 and CO_2 thus supplied are mixed in the molar ratio 1:1 and are assumed to react at 730°C to form CO and H_2, both reducing gases. The complete reaction equilibrium within the system at 730°C yields a calculated partial pressure of oxygen in the gases of 2.7×10^{-23} atm. Such a reducing gas mixture can provide effective protection against the reoxidation of liquid steel in the pool 53.

The foregoing arrangement permits molten steel to pass from ladle to mold with a near-minimum of contamination, near-optimum opportunity for removal of unwanted inclusions, and near-minimum opportunity for oxidation to occur. The preferred absence of casting powder and the use of an open-pour guiding shroud facilitate the obtention of a clean steel product.

Knowing the liquid steel head (ferrostatic height) in the secondary tundish 3 and the dimensions of the kissing-point gap 55 and the well nozzle 51, from a mass balance viewpoint under steady-state conditions at a given casting speed, it is possible to design the described tundishes and associated apparatus so as to provide a certain quantity of steel 63 in the secondary tundish 3 that generates a pool of liquid steel 53 over the desired surface contact area of the twin casting rolls 57, 59. This is usually expressed as the mold-level angle A (Figure 3) subtended by the meniscus of the pool 53 and the kissing-point gap 55. This angle A should preferably be selected to lie in the range about 30° to about 45°. The flow rate of liquid steel required is governed by ferrostatic height and cross-sectional area of the guiding shroud nozzle(s).

Located between the ends of the twin casting rolls 57, 59 are side dams 83 (Figure 4) whose concave arcuate sides 85, 87 conform in shape and dimension to the cylindrical peripheries of the rolls 57, 59. The side dams 83 serve to confine the ends of the steel pool 53. The dams 83 are preferably made of high-temperature-resistant refractory material. The top edge 89 of each of the dams 83 must be above the level of the meniscus of the steel pool 53 sufficiently to prevent any overflow, and should extend as close as feasible to the splash guard 5 so as to minimize the loss of the inert gas atmosphere. The bottom edge 91 should extend below the kissing-point gap 55 to just above the top edges of the stationary mold 10, so as to minimize the risk of any break-out between the dam 83 and the stationary mold 10. The dams 83 are designed to be movable transversely in either direction. They are illustrated in Figure 4 at the outer limit of their possible transverse movement; they may move inwardly from their positions at the ends of the rolls 57, 59 to reduce the width of the cast strand. Means (not shown), such as a suitable conventional

hydraulic piston/cylinder arrangement, may be provided to adjust the spacing between the dams 83 to accommodate varying widths of strand.

Rape-seed oil or other suitable lubricant is applied to the surface of each of the twin casting rolls 57, 59 via lubricant injectors 6. The lubricant tends to minimize the risk of adherence of steel droplets to the surfaces of the casting rolls 57 and 59, and tends to prevent sticker-type breakouts of the cast strand.

As the molten steel passes from the top of pool 53 to the gap 55, it begins to solidify. If the gap 55 is very narrow, say less than about 5 mm, the steel may be completely solidified at or near the kissing point between rolls 57, 59. However, at wider gap dimensions, the still hot, liquid core of the steel as it emerges downstream of the gap 55 will not permit the strand reliably to retain its shape; absent the precautions, the risk of break-out would be high. This fact has limited the use of conventional twin-roll casters to cast strand thicknesses of less than about 5 mm.

Positioned immediately downstream and underneath of the rolls 57 and 59 is a stationary mold 10 having a central channel 65 of rectangular cross-section whose narrow dimension is approximately equal to or very slightly smaller than the dimension of the gap 55 between the twin casting rolls 57 and 59. The width of the channel 65 may taper very slightly inwardly from top to bottom to accommodate thermal contraction and solidification shrinkage of the steel strand as it solidifies; the gap width may receive fine adjustment by machining the surfaces of the stationary copper mold 10.

The stationary mold 10 is preferably a water-cooled copper mold, i.e. its faces forming the interior

channel 65 are formed of copper; the balance of the mold structure may be made of steel. The mold 10 is shaped so that its upper concave surfaces 69 lie as close as possible to the casting rolls 57 and 59 above, and in particular so that the entry mouth 57 of the mold channel 65 is as close as possible to the kissing-point 55 between the casting rolls 57 and 59. The flow of mold cooling water may be adjusted so that heat flux extraction in the range of about 5 to about 30 cal/cm^2/sec is obtained. This range should be satisfactory for the range of casting thicknesses for which the equipment is designed.

For the casting of very thin strands, the stationary mold 10 may not be necessary. If the strand is solid as it leaves the twin casting rolls 57, 59, there is no need for the stationary mold 10, which can be removed and/or by-passed. However, the principal benefits of the present invention are obtained when the strand is wide enough to be cooled appreciably downstream of the casting rolls 57, 59, and when a series of reductions of such strand occur, as described below.

Cooling of the molten steel occurs over that portion of the peripheral cylindrical surface of each of the rolls 57, 59 subtended by angle A (Figure 3), and by the interior vertical faces 73 of the stationary mold 10. Further cooling occurs in a strand containment and secondary spray cooling station 11, to be further described below.

It is preferred that, at least for greater thicknesses of the cast strand, 90% or more of the solidification of the strand occur downstream of the casting rolls 57, 59. By providing most of the relatively rapid cooling required for solidification while maintaining dimensional integrity of the cast strand while its shell is still relatively thin (by using the stationary mold and

strand containment and secondary spray cooling station 11 to be described) it is possible to cast strands up to about 35 mm in thickness or even somewhat more than this, the casting of steel in such thicknesses permits a series of downstream reductions to take place (to be described further below) that permit at least a 3:1 thickness reduction relative to the initial thickness of the cast strand. This enables a final strip product to be produced of thickness up to about 12 mm or more with reasonably good metallurgical properties and good surface finish.

It can be seen from the drawing that the vertical faces 73 of the stationary mold provide a cooling area that is about equal to the cooling area provided by the cylindrical surface subtended by angle A of each of the twin casting rolls 57, 59. However, the ratio of cooling surface area of stationary mold to twin-roll caster cooling surface area, and the ratio of both to the strand containment cooling area to be described further below, may vary considerably according to the designer's preference, but I consider best results are obtained, at least for castings above 20 mm in thickness, if 90% or more of solidification of the cast strand occurs downstream of the casting rolls 57, 59. In any case, the additional provision of the stationary mold 10 to the layout can substantially increase the available primary cooling area for the steel being cast, as compared with conventional twin-roll caster design. This enables much wider gaps 55, 65 to be present between the twin rolls 57, 59 and the two opposed cooling blocks 64, 66 of the stationary caster 10 than is possible using conventional design.

For thicker castings (say 20 mm or more), end walls are preferably provided on the stationary mold to close the ends of the mold gap 65. For thinner castings (say 20 mm or less), end walls may be omitted and instead

water sprays may be provided to cool the edges of the cast strand 31 as it passes through the mold gap 65.

While reference herein is made to the mold 10 as being a "stationary" mold, it is to be understood that the two opposed cooling blocks 64, 66 of the stationary mold 10 could be designated to be moved towards and away from one another to accommodate varying thicknesses of casting. The same, of course, is true for the twin rolls 57 and 59; the gap 55 may be adjusted according to the casting thickness desired. Although the apparatus according to the invention can be used for making castings with a thickness as thin as about 5 mm or even somewhat less, some of the principal advantages of the invention are most markedly obtained when the thickness of the casting is relatively large, in about the 20 to 35 mm range or even somewhat higher.

Preferred alternative stationary mold designs are described in my copending U.S. patent application Serial No. , filed on

Immediately downstream of the stationary water-cooled copper mold 10 is a strand containment stage 11 comprising opposed pairs of horizontally rotatably mounted segmented rolls 29, one in each pair on either side of the cast strand 31 emanating from the stationary mold 10. These opposed rolls 29 are aligned with the exit port 52 of the stationary mold 10 and provide an opportunity for further cooling of the casting 31 before it reaches preferred reduction rolling temperature. The strand containment stage 11 may, for example, comprise 8 pairs of segmented rolls 29 located immediately below the extended water-cooled copper mold 10. Such segmented rolls may be of the same general type as used in conjunction with conventional oscillating slab casters.

The strand containment apparatus 11 along with the cooling surfaces of the stationary water-cooled mold 10 provide an effective metallurgical length (from the kissing point of the twin casting rolls 57, 59) of about 2100 mm for strand cast at 35 mm thickness. Equipment so designed will allow a calculated casting speed up to about 8 to 9 m/min for cast strand 35 mm thick and up to about 1 m/sec for strand 5 mm thick.

The widths of the gaps between opposed pairs of supporting rolls 29 for the strand containment apparatus 11 may be sequentially reduced, providing soft reduction for center-line segregation control. A battery of water/air mist spray nozzles 33 on either side of the roll pairs 29 provides spray cooling of the strand as it passes through the strand containment stage. The water spray may be omitted for the thinner cast strands if found to be unnecessary. The soft reduction in conjunction with the dynamic air-mist secondary spray cooling facilitates good external and internal quality of the strand. The designed heat flux removal from the secondary spray cooling is calculated to be in the range of about 10 cal/cm^2/sec to about 35 cal/cm^2/sec. The solidification constant of the cast strand is a function of spray water intensity and strand thickness. Calculated solidification constants are typically in the range of about 30 mm/$\sqrt{}$min to about 45 mm/$\sqrt{}$min for thicker cast strands.

A pair of opposed drive rolls 12 of 380 mm in diameter are located below the strand containment station 11 and just above the strand bending/unbending zone 13 (to be described) to regulate the speed of the cast steel strand 31 through subsequent stages.

The bending and unbending (redirection) zone or station 13 consists of three pairs of bending and unbending

rolls (to be described) to bend and unbend the strand from a vertical position to a horizontal position. The overall bending and unbending radius of the arc of travel of the strand 31 is preferably about 3000 mm.

As few as three pair of bending and unbending rolls can be used at redirection station 13 to change the orientation of the cast steel strand from the vertical to the horizontal. An offset bending roll pair 24, 26 are followed by an opposed roll pair 28, 30, and finally, by an offset unbending roll pair 32, 34. Note that the roll pairs 24, 26 and 32, 34 comprise offset, rather than opposed, rolls. The rolls 26, 30 and 34 that are located on the interior of the arc of travel of the steel strand 31 through the redirection station 13 are spaced more closely together than are the rolls 24, 28, 32 on the exterior of the arc of travel of the steel strand 31 through the redirection station 13. This arrangement is effective to redirect the steel strand 31 passing through the redirection station 13, with a minimum of redirection rolls being required - as few as three pair, as illustrated, can effect a smooth redirection of the steel strand 31.

It is an aspect of the invention that the cast strand 31 is preferably reduced in thickness by hard reduction to improve dimensional uniformity, surface smoothness, steel microstructure and metallurgical quality. Conventionally, a 3-to-1 reduction is desirable to achieve optimum metallurgical quality at minimum expense so as to obtain preferred physical properties of the steel. To this end, a roughing stage and subsequent finishing stages are provided according to the preference of the rolling mill designer.

In the exemplary mill layout herein described, the cast strand 31 passes first through a roughing mill 15 and then subsequently through finishing mills 19 and 21.

Depending upon space requirements, the first reduction could occur while the strand is travelling vertically, in which case the drive roll pair 12 would be replaced by a hot reduction rolling stand equipped with a conventional hydraulic descaler. However, it is conventional to change the orientation of the steel strand from vertical to horizontal before commencing reduction, and that is the arrangement illustrated in Figure 1.

A hydraulic descale box 14 is used to descale the strand 31 prior to entering the first reduction pass through a 4-high roughing stand 15 of conventional design (except as to the width of the roll gap).

The in-line 4-high roughing stand 15 is used to roll as-cast strand with a reduction ratio of preferably about 0.3 to 0.5. The work roll and back-up roll diameters are preferably about 635/700 mm and 1925/2000 mm, respectively. The barrel length is preferably about 1925 mm. The mill drive may be equipped with 1600 horse power with a maximum roll torque of 3.5×10^5 fl-lb and a maximum roll force of 16 MN/m.

Downstream of the roughing stand 15 is a first laminar flow cooling control stage or station 16. The cooling stage 16 is designed, together with the immediately following induction furnace 17 to be described, for the purpose of achieving preferred metallurgical results. Specifically, once a significant amount of energy has imparted to the strand 31 by the roughing reduction in roughing stand 15, the laminar flow cooling station 16 reduces the temperature of the intermediate steel strip to

a value below the Ar_1 temperature. Subsequently, in the induction furnace 17, the temperature of the intermediate steel strand is brought up to a level above the Ar_3 temperature. This enables recrystallization to occur in the steel. Subsequent rolling in the finishing roll stands to be described below enables a relatively fine grain structure to be achieved with suitable surface properties on the finished steel strip. Such strip is characterized by a combination of metallurgical properties that cannot be achieved by conventional twin roll casting processes.

Not only should the induction furnace 17 bring the temperature of the intermediate strip to a value above the Ar_3 temperature, but such exit temperature from the induction furnace 17 should be at or above the desired strip entry temperature at the subsequent finishing roll stands. Designed heat flux removal from laminar water flow at the station 16 is preferably in the range of about 10/cal/cm²/sec to about 35 cal/cm²/sec. The effective cooling zone is preferably about 2000 mm. This laminar flow cooling station (which is normally used in conjunction with the reheat furnace 17) may not have to be operated for the rolling of some grades of steel, but will be important in the thermomechanical rolling of high-strength steels.

The use of the inductive heating furnace 17 downstream of cooling station 16 is particularly important for thin strip production because of severe temperature drop during the earlier upstream stages. An induction edge heater (not shown) within or associated with furnace 17 can also be used to compensate for the severe temperature drop of wider strand. Input of heat flux is preferably in the range of about 10 cal/cm²/sec to 35 cal/cm²/sec. The effective reheating zone is about 3000 mm.

A second hydraulic descale box 18 is used to descale the strip 31 following its reheating by the reheat furnace/edge heater 17 and prior to entering into the first 4-high finishing roll stand 19.

The in-line 4-high finishing stand 19 rolls the strip 31 with a reduction of preferably about 0.1 to 0.3. The work roll and back-up roll diameters are preferably about 500/600 mm and 1020/1100 mm, respectively. The barrel length is preferably about 1925 mm. The mill drive may be of about 1200 hp with a maximum roll torque of about 7.5 x 10^5 fl-lb and a maximum roll force of about 10 MN/m. The first 4-high finishing stand 19, is preferably equipped with hydraulic automatic gauge control (AGC), and work roll shifting and bending capability for strip thickness and shape control.

A hydraulic descale box 20 is used to descale the strip 31 prior to entering into a second 4-high finishing roll stand 21.

The in-line 4-high finishing stand 21 is used to impart a final finishing reduction to the strip 31, with a preferred reduction ratio of about 0.03 to 0.2. The finished strip thickness ranges from about 1 mm to about 12 mm. Work roll and back-up roll diameters for stand 21 are preferably about 500/600 mm and 1020/1100 mm respectively. The barrel length is preferably about 1925 mm. The mill drive for the finishing stand 21 may provide about 450 hp with a maximum roll torque of about 1.5 x 10^5 ft-lb and a maximum roll force of about 10 MN/m. The second 4-high finishing stand 21 is preferably equipped with hydraulic AGC, and work roll shifting and bending capability.

A second laminar water flow cooling station 22 downstream of the final finishing stand 21 is designed for the purpose of accelerated controlled cooling to achieve the desired downcoiler temperature. Designed heat flux removal from laminar water flow cooling is preferably in the range of about 10/cal/cm^2/sec to 40 cal/cm^2/sec. The effective cooling zone is about 5000 mm.

A conventional shear 23 and conventional downcoiler 27 terminate the rolling line. The strip after final cooling is wound up in the down-coiler 24 and then cut to length by the shear 23. Other optional equipment that might be found in a conventional rolling mill (such as edge trimmers, etc.) are not shown for purposes of simplification, it being understood that one or more of such optional items of equipment may be provided or omitted at the discretion of the mill designer, according to the preferred practice to be followed in the mill.

An arrangement of the foregoing type should be able to produce cast strand from about 5 mm up to at least about 35 mm in thickness, and perhaps, depending upon desired properties of the final product, up to about 40 to 50 mm in thickness. For cast steel strand above about the 40 mm thickness range, the described arrangement is expected not to be as economically attractive as conventional mills that cast steel in about the 2-inch range.

At the smaller casting thicknesses, however, the present invention offers much more versatility than a conventional twin-roll caster. Because of the additional cooling provided by the stationary mold and the immediately following strand containment station, as compared with the very limited cooling afforded by a conventional twin-roll caster, the caster and associated equipment herein described permit the casting of steel strand at a high casting speed

over a wide range of thicknesses, permitting downstream reduction rolling to improve dimensional, surface and metallurgical quality, and affording a relatively wide range of end product thicknesses.

The fact that the casting thickness of strand cast using the equipment and technique according to the invention is oversize relative to cast strand produced by conventional twin-roll casters means that at least two, and preferably at least three, reductions of the steel strand can and should occur downstream of the caster, thereby improving the dimensional, surface and metallurgical qualities of the finished coiled strip product (obviously the strand could be cut to length and kept flat, but coil is the most usual product of this kind of process). It is well understood that a series of reductions in the rolling of steel plate or strand improves the microstructure and other metallurgical properties of the final product, and thus the present invention is seen to afford a higher quality of product than can be obtained using conventional twin-roll casters, with annual production of up to one million tons.

Variants on the specific layout illustrated in the drawing and described above will readily occur to those skilled in the art; the scope of the invention is as defined in the appended claims.

EXAMPLE 1

For the purposes of this example, the apparatus arrangement of Figure 1 is assumed, with the spacing and processing length of constituent elements of the apparatus dimensioned as indicated in Figure 2.

Set forth below are various specifications of the equipment that apply to the Figure 2 apparatus. The values

obtained were computed using a computer simulation of the apparatus, and apply over the range of castings for which the preferred embodiment of the apparatus is designed to be used, namely castings ranging from 5 mm in thickness to 35 mm in thickness. Following these general specifications, a series of three more specific examples will be reviewed in greater detail: Example 1A, comprising equipment arranged in accordance with Example 1 set to obtain a casting thickness of 35 mm; Example 1B, for the same equipment, set to obtain a casting thickness of 10 mm; and Example 1C, for the same equipment, set to obtain a casting thickness of 5 mm.

The graphs of Figures 5A through 5C apply to the 35 mm casting (Example 1A); those of Figures 6A to 6C apply to the 10 mm casting (Example 1B), and those of Figures 7A to 7C apply to the 5 mm casting (Example 1C).

The following, then, are general specifications of the Figure 2 apparatus applicable to the range of castings from 5 to 35 mm in thickness:

Annual capacity:	0.5 to 1.0 million tons (varies with product mix)
Finished strip thickness:	1.0 to 12.0 mm (depends on casting thickness)
Product width:	about 900 to about 1830 mm
Coil weight:	about 15 to 40 metric tons
Specific coil size:	850 to 1250 PIW
Twin roll strand thickness:	5 to 35 mm
Twin roll casting speed:	8.5 to 55 m/min (depends on casting thickness)
Heat size:	100 to 150 metric tons

Steel grades:	carbon, stainless, HSLA, and drawing quality steels
Applications:	cold rolled, structural, coiled plate, and other industrial steels
Twin roll diameter:	1500 mm
Twin roll rotating speed:	1.5 to 12 rpm (depends on casting thickness)
Stationary water-cooled copper mold length:	900 mm
Mold level (Angle A):	35° to 45°
Primary cooling water flow rate:	500 to 1000 GPM
Strand containment length:	1200 mm
Support roll diameter:	100 mm
Inter-roll spacing:	130 mm
Metallurgical length (below kissing point of twin rolls):	2100 mm
Secondary spray cooling:	air-mist cooling
heat-extraction capacity	10 to 30 cal/cm^2 sec
Strand drive roll diameter:	380 mm
Bending radius:	3000 mm
Bending roll diameters:	300 to 500 mm, at designer's option
4-high roughing stand:	
Descaling:	hydraulic type
Work roll diameter:	635 to 700 mm
Work roll barrel length:	1925 mm
Back up roll diameter:	1290 mm
Back up roll barrel length:	1925 mm
Thickness reduction ratio:	0.3 to 0.5
Roll force (max.):	16 MN/m
Main drive:	1600 hp (880 kW)
Roll torque:	3.48 x 10^5 ft-lb

1st laminar cooling control:	
Length:	2000 mm
Heat-extraction capacity:	10 to 35 cal/cm^2 sec
Roller hearth furnace	
Length:	3000 mm
Heating medium:	inductive
4-high finishing rolling stands:	
Descaling:	hydraulic type
Work roll diameter:	500 to 600 mm
Work roll barrel length:	1925 mm
Back up roll diameter:	1020 mm
Back up roll barrel length:	1925 mm
Thickness reduction:	first stand: 0.2 to 0.4 second stand: 0.02 to 0.2
Additional features:	hydraulic AGC; work roll shifting and bending
Roll force:	10 MN/m
Main drive: first stand:	1200 hp (670 kW)
second stand:	450 hp (240 kW)
Roll torque: first stand:	7.32 x 10^5 ft-lb
second stand:	1.427 x 10^5 ft-lb
2nd laminar cooling control:	
Length:	5000 mm
Heat flux extraction capacity:	10 to 40 cal/cm^2 sec

EXAMPLE 1A:

The following set of calculated values apply to a computer simulation of the casting and related processing steps illustrated in Figures 1 and 2 for a mill having the parameters given in Example 1, and with a casting thickness of 35 mm.

For this particular example, it is assumed that the tunnel furnace 17 and first laminar flow cooling unit 16 are not operating. Accordingly, the steel strand passing

through these units will lose heat only through the conduction, convection and radiation losses associated with the idle condition of laminar flow unit 16 and tunnel furnace 17. The second laminar flow unit 22, however, is assumed to be operating for the purposes of this example. The following values were assumed or calculated from the computer simulation used:

Cast Steel Carbon Content,	0.04 Wt%
Liquidus Temperature, 1510°C, Solidus Temperature	1434°C

Twin-roll caster parameters:

Twin Roll Cooling Water Flow Rate,	500 GPM per roll
Mold Level (Angle A),	40°
Heat Transfer Coefficient in Water Slot,	2.42 $cal/cm^2/sec/°C$
Overall Heat Transfer Coefficient,	0.1311 $cal/cm^2/sec/°C$
Mold Water Temperature Difference (between entrance water temperature and exit water temperature in twin rolls),	1.745°
Heat Flux,	190 $cal/cm^2/sec$
Steel Thermal Conductivity,	.057 cal/cm/sec/°C
Steel Specific Heat,	0.16 cal/g/°C
Average Shell Temperature,	1000°C
Roll Rotation Speed,	11°/sec
Roll Rotation Speed,	1.817 rpm

Stationary Copper Mold and Strand Containment Parameters:

Casting Speed (m/min)	8.57
Solidifying Shell Thickness at Kissing Point (mm)	5.74
Strand Thickness (mm)	35
Heat Flux Removal by Stationary Water Cooled Copper Mold ($cal/cm^2/sec$)	30
Heat Flux Removal by Secondary Spray Cooling ($cal/cm^2/sec$)	30
Average Exit Strand Temperature (at exit of strand containment) (°C)	1315
Solidification Constant ($mm/\sqrt{min}$)	35.2

Roll Force Calculations for Roll Stands

	Roughing Stand	First Finishing Stand	Second Finishing Stand
Reduction Ratio	0.50	0.30	0.20

Entry Gauge (mm)	35	17.5	12.25
Exit Gauge (mm)	17.5	12.25	9.80
Average Strand Entry Temperature (°C)	1124	935	872
Average Strand Exit Temperature (°C)	1127	931	851
Entry Speed (m/min)	8.57	17.14	22.12
Exit Speed (m/min)	17.14	22.12	27.65
Angle of Roll Bite (°)	15.09	8.43	5.63
Strain Rate (1/sec)	2.14	3.35	3.70
Roll Force (MN/m)	11	9.5	7.6
Roll Force (tons)	2075	1785	1430
Power (hp)	643	487	333
Power (KW)	354	268	183
Roll Torque (ft-lb)	390,000	184,000	107,000

1st Laminar Flow Cooling Zone Heat Flux Removal
(not operating for this example)

Strand Speed (m/min)	17.14
Strand Gauge (mm)	17.5
Heat Flux Removed (cal/cm²/sec) (radiation loss only)	5.00
Average Strand Entry Temperature (°C)	1115
Average Strand Exit Temperature (°C)	1084

Inductive Edge Heater and Reheat Furnace
(not operating for this example)

Strand Speed (m/min)	17.14
Strand Gauge (mm)	17.5
Heat Flux Input (heat loss) (cal/cm²/sec)	-5.00
Average Strand Entry Temperature (°C)	1066
Average Strand Exit Temperature (°C)	1015

2nd Laminar Flow Cooling Zone Heat Flux Removal

Strand Speed (m/min)	27.6
Strand Gauge (mm)	9.8
Heat Flux Removed (cal/cm²/sec)	15
Average Strand Entry Temperature (°C)	836
Average Strand Exit Temperature (°C)	613
Downcoiler entry temperature (°C)	597

Referring to Figure 5A, the graph plotted shows half-strand thickness of the cast steel strand relative to the downstream distance from the top of the twin roll caster. By the time that the cast steel strand has reached point K (the kissing point of casting rolls 57, 59), the shell is of thickness 5.7 mm. By the time the strand reaches point E in the upper portion of strand containment

stage 11, it has completely solidified, and its thickness has reached a stable uniform dimension, which is 35 mm for the complete strand thickness in this example, and therefore 17.5 mm for the half-strand thickness illustrated in Figure 5A. That thickness is maintained by the strand containment apparatus 11 until the cast strand reaches the first roughing stand 15 at point R along the curve of Figure 5A. At the roughing stand, it is assumed that a 50% reduction is given to the casting, and that its output thickness is 8.75 mm for the half-strand (17.5 mm for the full thickness of the strand). This dimension is maintained until the strand reaches the first finishing mill F1, where it is given a first finishing reduction and then, when it reaches the second finishing mill 21 at point F2, it is given a second finishing reduction, reaching its final finished thickness thereafter.

As the strand is reduced in thickness, so its speed of travel increases. This fact is reflected in Figure 5B, which shows the successive increases in strand speed as the strand passes successive reductions. The speed up to the point of entry into roughing roll stand 15 is the as-cast speed that is regulated by drive rolls 12. The letters R, F1 and F2 correspond to the reduction points previously identified for Figure 5A, and show the successive speed increases of the strand as it passes through its initial roughing reduction at point R and successive finishing reductions at points F1 and F2.

In Figure 5C, temperatures at three positions of the cast steel strand are calculated to represent the thermal profile of the strand. Curve S plots the surface temperature of the steel strand; Curve A plots the average temperature through the steel strand, and Curve C plots the centre-line temperature for the steel strand. The temperatures are plotted relative to the downstream distance

from the top of the twin-roll caster to the downcoiler, as is the case for the other graphs in the accompanying drawings.

The response of surface temperature S to the sequence of processing stages through which the strand passes is more pronounced (as seen in the graph of Figure 5C) than that of average temperature A or that of centre-line temperature C. Between point M at the entry point of the strand containment apparatus 11 and point P at the exit of the strand containment unit 11, the surface temperature variations imparted to the surface of the steel strand by the sequential contact of the steel strand with segmented rolls 29 and by the cooling spray 33 appear quite clearly in Curve S. Curve S also shows the surface temperature fluctuations imparted to the cast steel strand due to effect of roll surface contact cooling as it passes through the sequence of redirection roll pairs 24, 26; 28, 30; and 32, 34. These three successive stages are represented by points B1, B2 and B3 in Figure 5C. (For the purpose of plotting curve S, the drive rolls 12 have been assumed to be disengaged. If they were engaged, an additional "blip" in the curve S would be expected to occur.) Points R, F1 and F2 on Figure 5C correspond to the points similarly labelled in Figures 5A and 5B.

EXAMPLE 1B

Example 1B is identical to Example 1A, except that instead of a 35 mm as-cast strand thickness, the thickness is set in the computer simulation at 10 mm. The computed parameters for Example 1B are as follows:

Cast Steel Carbon Content,	0.04 Wt%
Liquidus Temperature, 1510°C, Solidus Temperature	1434°C

Twin-roll caster parameters:

Twin Roll Cooling Water Flow Rate,	500 GPM per roll
Mold Level (Angle A),	40°
Heat Transfer Coefficient in Water Slot,	2.42 $cal/cm^2/sec/°C$
Overall Heat Transfer Coefficient,	.197 $cal/cm^2/sec/°C$
Mold Water Temperature Difference (between entrance water temperature and exit water temperature in twin rolls),	9.2°
Heat Flux,	285 $cal/cm^2/sec$
Steel Thermal Conductivity,	.057 cal/cm/sec/°C
Steel Specific Heat,	0.16 cal/g/°C
Average Strand Shell Temperature,	1127°C
Roll Rotation Speed,	38.2°/sec
Roll Rotation Speed,	6.37 rpm

Stationary Copper Mold and Strand Containment Parameters:

Casting Speed (m/min)	30
Solidifying Shell Thickness at Kissing Point (mm)	2.8
Strand Thickness (mm)	10
Average Exit Strand Temperature (at exit of strand containment) (°C)	1244
Solidification Constant ($mm/\sqrt{min}$)	48.3

Roll Force Calculations for Roll Stands

	Roughing Stand	First Finishing Stand	Second Finishing Stand
Reduction Ratio	0.50	0.30	0.10
Entry Gauge (mm)	10.00	5.00	3.50
Exit Gauge (mm)	5.00	3.50	3.15
Average Strand Entry Temperature (°C)	1065	1036	920
Average Strand Exit Temperature (°C)	1038	979	884
Entry Speed (m/min)	30	60	85.7
Exit Speed (m/min)	60	85.7	95.2
Angle of Roll Bite (°)	7.20	4.41	2.13
Strain Rate (1/sec)	12.54	21.94	16.82
Roll Force (MN/m)	12.34	7.84	3.54
Roll Force (tons)	2324	1410	667
Power (hp)	1200	716	220.5
Power (KW)	659	394	121.3
Roll Torque (ft-lb)	261,100	77,560	19,960

1st Laminar Flow Cooling Zone Heat Flux Removal
(not operating for this example)

Strand Speed (m/min)	60
Strand Gauge (mm)	5.00
Heat Flux Removed ($cal/cm^2/sec$) (radiation loss only)	5.00
Average Strand Entry Temperature (°C)	1024
Average Strand Exit Temperature (°C)	991

Inductive Edge Heater and Reheat Furnace

Strand Speed (m/min)	60
Strand Gauge (mm)	5.00
Heat Flux Input (cal/cm²/sec)	10.00
Average Strand Entry Temperature (°C)	975
Average Strand Exit Temperature (°C)	1041

2nd Laminar Flow Cooling Zone Heat Flux Removal

Strand Speed (m/min)	85.7
Strand Gauge (mm)	3.15
Heat Flux Removed (cal/cm²/sec)	20
Average Strand Entry Temperature (°C)	884
Average Strand Exit Temperature (°C)	582
Downcoiler entry temperature (°C)	566

The graphs of Figures 6A, 6B and 6C are to be understood in exactly the same way as the graphs of Figures 5A, 5B and 5C, except that the strand thickness as cast for Figures 6A, 6B and 6C is 10 mm instead of 35 mm for Figures 5A, 5B and 5C.

There is one significant difference between Examples 1A and 1B, namely the fact that for the 10 mm as-cast steel strand, the tunnel furnace 17 is operated, whereas it was not operated for the 35 mm example 1A. This difference is graphically illustrated in Figure 6C, which shows a gradual temperature increase beginning at point T when the strand reaches the entry port of the tunnel furnace 17.

EXAMPLE 1C

Example 1C is identical to Example 1B, except that instead of a 10 mm as-cast strand thickness, the thickness is set in the computer simulation at 5 mm. The computed parameters for Example 1C are as follows:

Cast Steel Carbon Content,	0.04 Wt%
Liquidus Temperature, 1510°C, Solidus Temperature	1434°C

Twin-roll caster parameters:

Twin Roll Cooling Water Flow Rate,	500 GPM per roll
Mold Level (Angle A),	40°
Heat Transfer Coefficient in Water Slot,	2.42 cal/cm²/sec/°C
Overall Heat Transfer Coefficient,	.197 cal/cm²/sec/°C
Mold Water Temperature Difference (between entrance water temperature and exit water temperature in twin rolls),	19.6°
Heat Flux,	335 cal/cm²/sec
Steel Thermal Conductivity,	.057 cal/cm/sec/°C
Steel Specific Heat,	0.16 cal/g/°C
Average Strand Shell Temperature,	1192°C
Roll Rotation Speed,	69.5°/sec
Roll Rotation Speed,	11.6 rpm

Stationary Copper Mold and Strand Containment Parameters:

Casting Speed (m/min)	54.5
Solidifying Shell Thickness at Kissing Point (mm)	1.93
Strand Thickness (mm)	5
Heat Flux Removal by Stationary Water Cooled Copper Mold (cal/cm²/sec)	30
Heat Flux Removal by Secondary Spray Cooling (cal/cm²/sec)	30
Average Exit Strand Temperature (at exit of strand containment) (°C)	1173
Solidification Constant (mm/√min)	83.7

Roll Force Calculations for Roll Stands

	Roughing Stand	First Finishing Stand	Second Finishing Stand
Reduction Ratio	0.50	0.30	0.10
Entry Gauge (mm)	5.00	2.50	1.75
Exit Gauge (mm)	2.50	1.75	1.58
Average Strand Entry Temperature (°C)	951	920	788
Average Strand Exit Temperature (°C)	944	914	820
Entry Speed (m/min)	54.5	109.1	155.9
Exit Speed (m/min)			
Angle of Roll Bite (°)	5.09	3.12	1.51
Strain Rate (1/sec)	32.3	56.5	43.3
Roll Force (MN/m)	13.12	7.5	3.67
Roll Force (tons)	2471	1413	691
Power (hp)	1636	923	294
Power (KW)	900	508	161.6
Roll Torque (ft-lb)	196,300	54,960	14,610

1st Laminar Flow Cooling Zone Heat Flux Removal
(not operating for this example)

Strand Speed (m/min)	109.1
Strand Gauge (mm)	2.50
Heat Flux Removed (cal/cm²/sec) (radiation loss only)	5.00
Average Strand Entry Temperature (°C)	930
Average Strand Exit Temperature (°C)	897

Inductive Edge Heater and Reheat Furnace

Strand Speed (m/min)	109.1
Strand Gauge (mm)	2.50
Heat Flux Input (cal/cm²/sec)	15
Average Strand Entry Temperature (°C)	880
Average Strand Exit Temperature (°C)	1038

2nd Laminar Flow Cooling Zone Heat Flux Removal

Strand Speed (m/min)	109.1
Strand Gauge (mm)	1.58
Heat Flux Removed (cal/cm²/sec)	10
Average Strand Entry Temperature (°C)	805
Average Strand Exit Temperature (°C)	660
Downcoiler entry temperature (°C)	646

The graphs of Figures 7A, 7B and 7C are to be understood in exactly the same way as the graphs of Figures 6A, 6B and 6C, except that the strand thickness as cast for Figures 6A, 6B and 6C is 5 mm instead of 10 mm for Figures 6A, 6B and 6C.

In the foregoing discussion, I have used the terms "strand" and "strip" to a certain extent interchangeably. The steel as cast is a properly finished product ready for shipment, it is a "strip". In between, it is an intermediate strip product that I have sometimes referred to as a strand, sometimes as a strip.

I CLAIM:

1. A method of casting and processing steel comprising

forming and maintaining to the end of the casting run, a pool of molten steel above the gap between substantially identical twin rolls of a twin-roll caster;

rotating the rolls at substantially identical speeds in opposite senses downwardly toward the gap above which the pool of molten steel lies;

directing the cast strand into and through the mouth of a stationary mold located immediately adjacent, underneath and downstream of the twin rolls, said mouth being of a width substantially identical to the thickness of the cast strand;

cooling the cast strand as it passes through the gap between the opposed segments of the stationary mold; and

further processing the strand downstream of the stationary mold to form a steel strip product.

2. The method of claim 1, wherein the further processing comprises hard reduction rolling of the strand.

3. The method of claim 2, wherein the further processing further comprises directing the strand at the exit of the stationary mold through a series of cooling rolls thereby further cooling the strand as it passes between the cooling rolls prior to hard reduction rolling of the strand.

4. The method of claim 3 additionally comprising spraying the cast strand with water as it passes between the cooling rolls.

5. The method as defined in claim 1, wherein the gap between the twin casting rolls and between the opposed

segments of the stationary mold is selected to be in the range about 3 mm to about 50 mm.

6. The method as defined in claim 2, wherein the gap between the twin casting rolls and the opposed segments of the stationary mold is selected to be in the range about 5 mm to about 35 mm.

7. The method as defined in claim 2, comprising cooling the twin rolls and stationary mold by passing a flow of cooling water through the interior of the twin rolls and of the stationary mold.

8. The method as defined in claim 2, comprising applying a lubricant to the surfaces of the twin rolls before those surfaces enter the pool of molten steel above the gap between the twin rolls.

9. The method as defined in claim 2, comprising grinding the surfaces of the twin rolls continually thereby to maintain a desired profile and smoothness of the roll surfaces.

10. The method as defined in claim 2, comprising applying heat to the surfaces of the twin rolls to raise the surface temperature thereof just prior to those surfaces moving into contact with the pool of molten steel above the gap between the twin rolls thereby to prevent or inhibit distortion of the roll surfaces due to sudden thermal expansion when they come into contact with the pool of molten steel.

11. The method of casting and rolling steel to form a steel strip product comprising

forming and maintaining to the end of the casting run a pool of molten steel above the gap between substantially identical twin rolls of a twin-roll caster;

rotating the rolls at substantially identical speeds in opposite senses downwardly toward the gap above which the pool of molten steel lies;

directing the cast strand into and through the mouth of a stationary mold located immediately adjacent, underneath and downstream of the twin rolls, said mouth being of a width substantially identical to the thickness of the cast strand;

cooling the cast strand as it passes through the gap between the opposed segments of the stationary mold; and

reducing the cast strand in thickness by a series of hard reductions to form steel strip having a thickness of about one-third or less the thickness of the cast strand.

12. The method as defined in claim 11, wherein the reducing comprises reducing the cast strand in a roughing mill and then further reducing the intermediate steel strip product at the exit of the roughing mill in two successive finishing reductions.

13. The method as defined in claim 12, wherein the roughing reduction is of the order of 30% to 50%.

14. The method as defined in claim 13, additionally comprising cooling the intermediate strip product after it exits the roughing mill and then reheating the strip before the first finishing reduction.

15. The method as defined in claim 14, wherein the cooling is laminar flow cooling.

16. The method as defined in claim 15, wherein the strip is cooled by the laminar flow cooling to a temperature

below the Ar_1 and is then reheated in the reheating step to a temperature above the Ar_3.

17. The method as defined in claim 16, additionally comprising cooling the strip after the second finishing reduction.

18. The method as defined in claim 17, wherein the cooling following the second finishing reduction is laminar flow cooling.

19. The method as defined in claim 11, wherein solidification of the strand occurs less than about 10% by contact with the twin rolls and at least about 90% downstream of the gap between the twin rolls.

20. The method as defined in claim 2, wherein solidification of the strand occurs less than about 10% by contact with the twin rolls and at least about 90% downstream of the gap between the twin rolls.

21. The method as defined in claim 2, comprising water spraying the side of the strand as it passes through the gap between the segments of the stationary mold.

22. The method as defined in claim 2, wherein the surface of each twin roll located between the meniscus of the pool of molten steel and the gap between the twin rolls is in the range about 25° to about 50°.

23. The method as defined in claim 2, wherein the surface of each twin roll located between the meniscus of the pool of molten steel and the gap between the twin rolls is in the range about 30° to about 45°.

24. The method as defined in claim 2, wherein the strand passes through the stationary mold at the rate of about 1 to about 6 tonnes per minute.

25. The method as defined in claim 8, wherein the lubricant is a selected vegetable oil.

26. The method as defined in claim 25, wherein the lubricant is rapeseed oil.

27. The method as defined in claim 2, comprising soft reducing the cast strand prior to reduction thereof, for segregation control thereof.

28. The method of claim 2, wherein the metallurgical length is selected to be between about 0 and 3 m.

29. The method of claim 8, wherein the casting occurs in the absence of casting powder.

30. The method of claim 1, wherein molten steel is supplied to the pool in an open pour.

31. The method of claim 30, wherein the open pour occurs in the presence of an inert gaseous atmosphere covering the surface of the pool.

32. The method of claim 30, wherein the open pour occurs in the presence of a reducing gaseous atmosphere covering the surface of the pool.

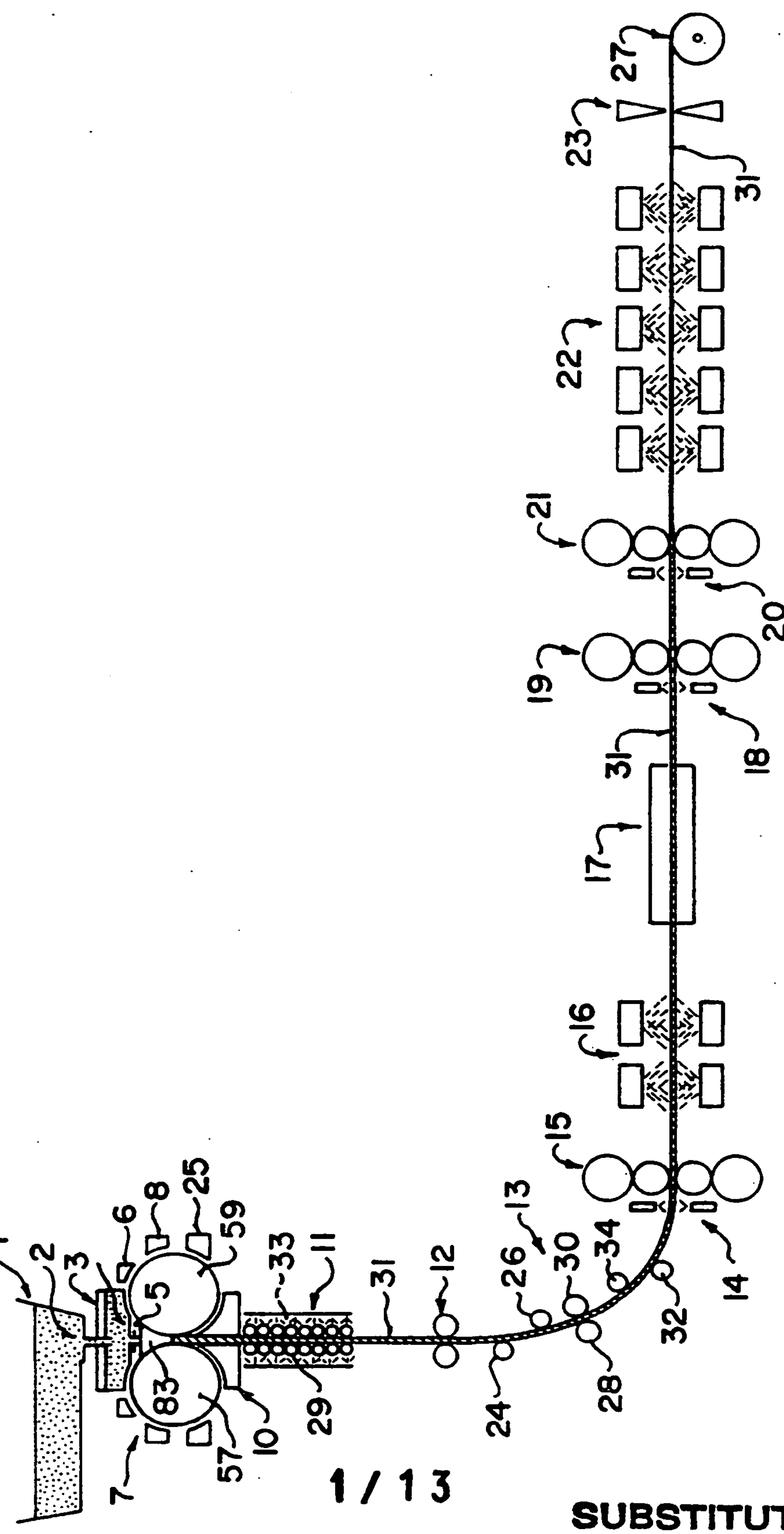

FIG. 1

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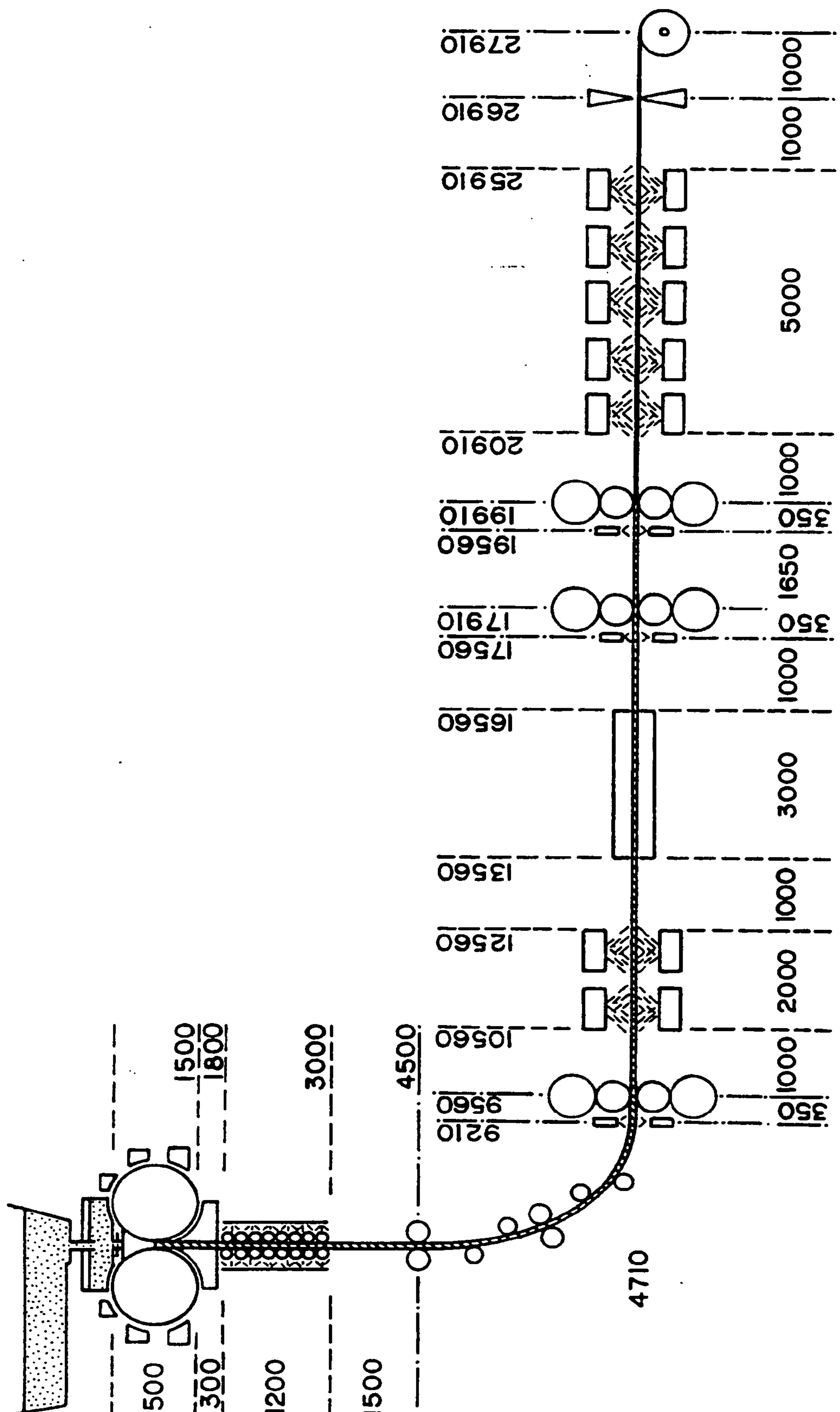
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1000
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1500

FIG. 2

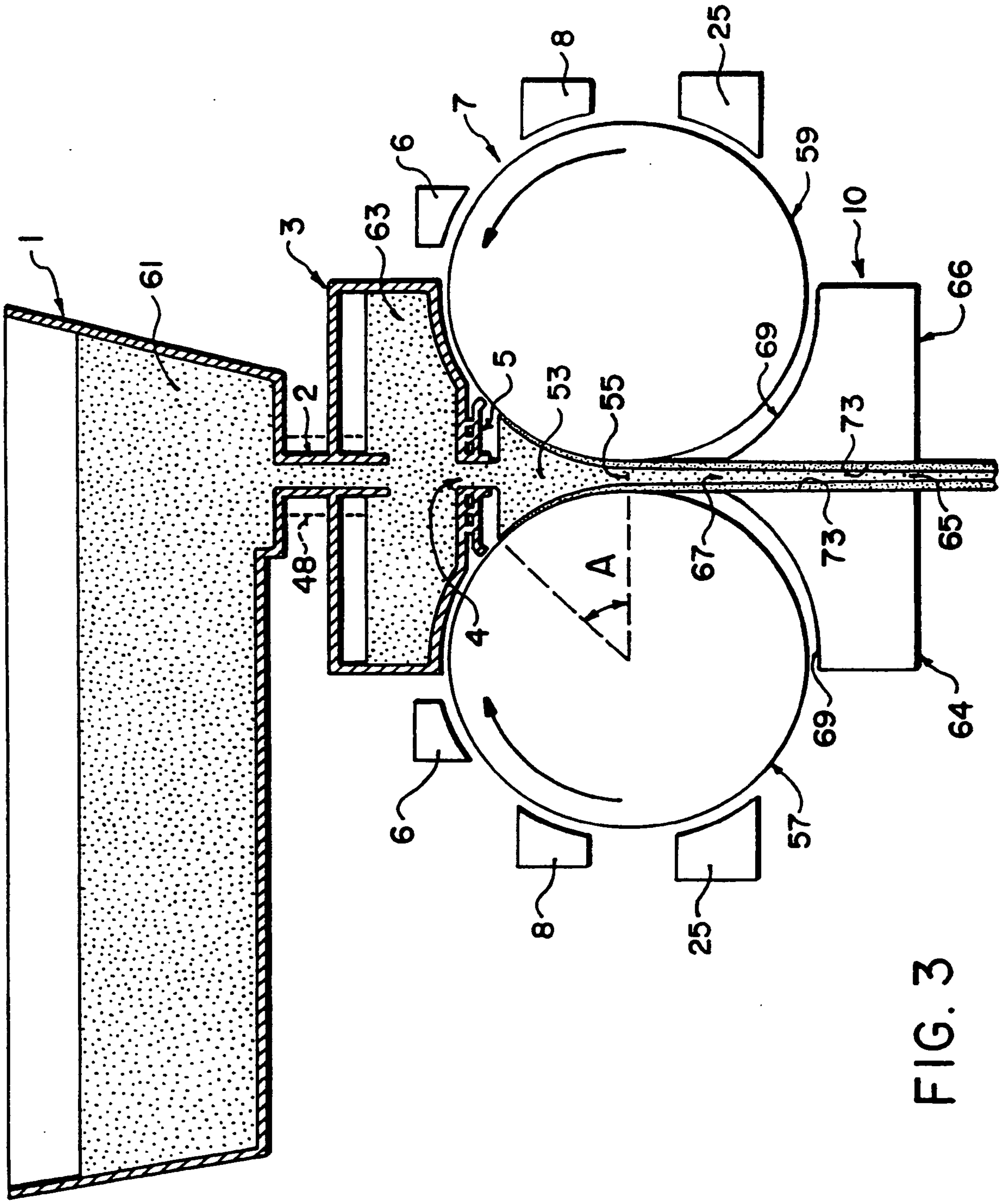

FIG. 3

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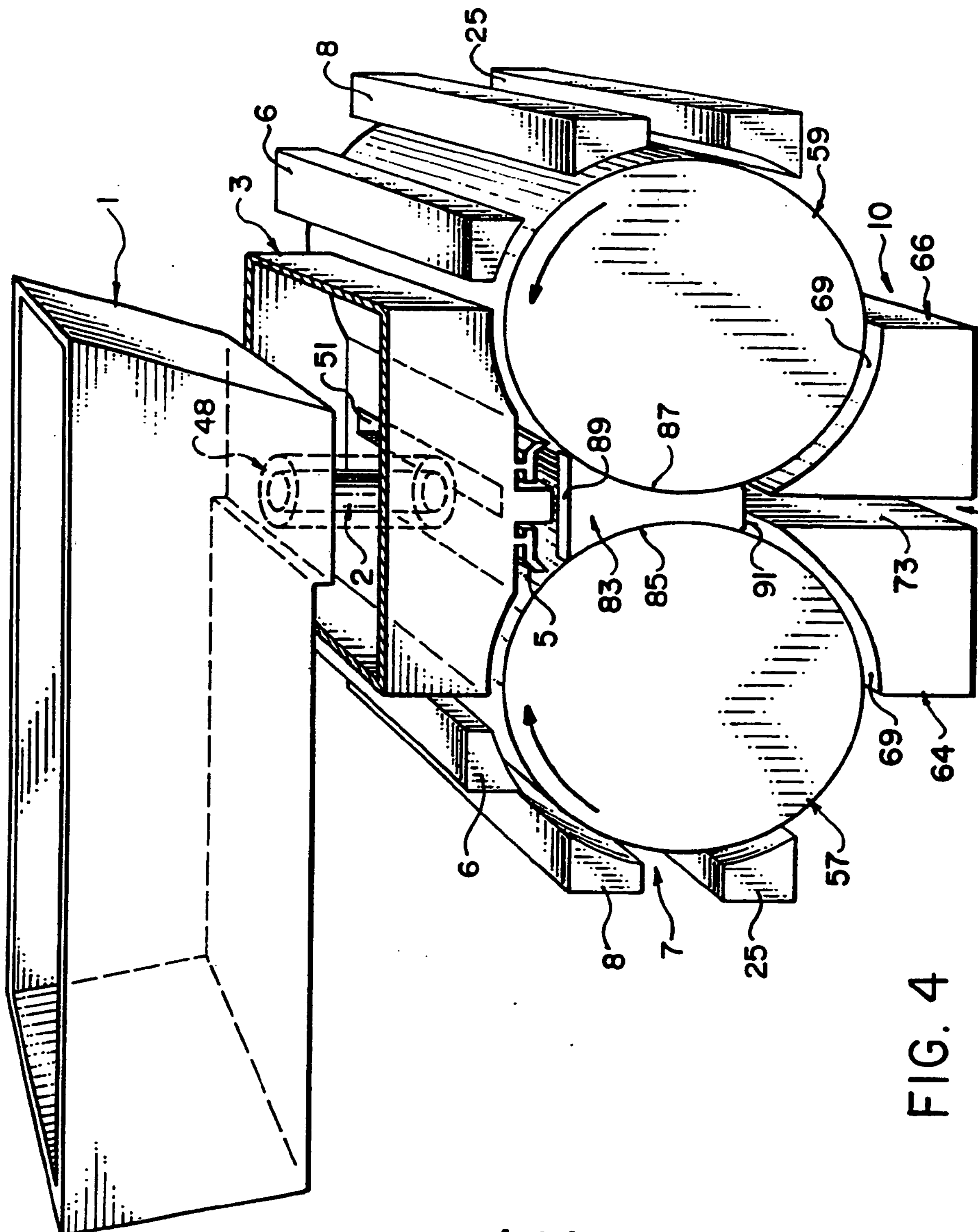

FIG. 4

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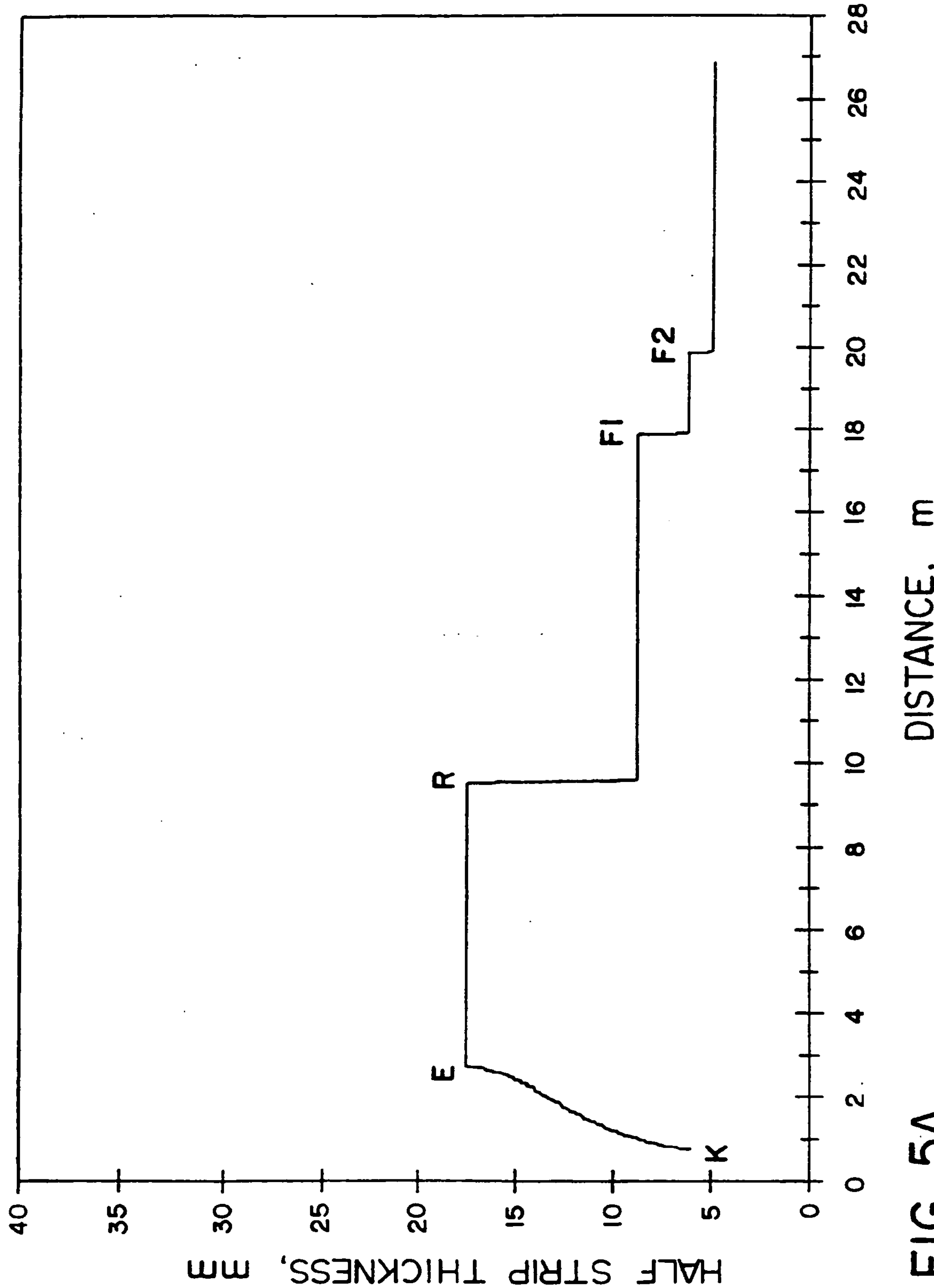
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R
FI
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20
25
30
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2
4
6
8
10
12
14
16
18
20
22
24
26
28

FIG. 5A

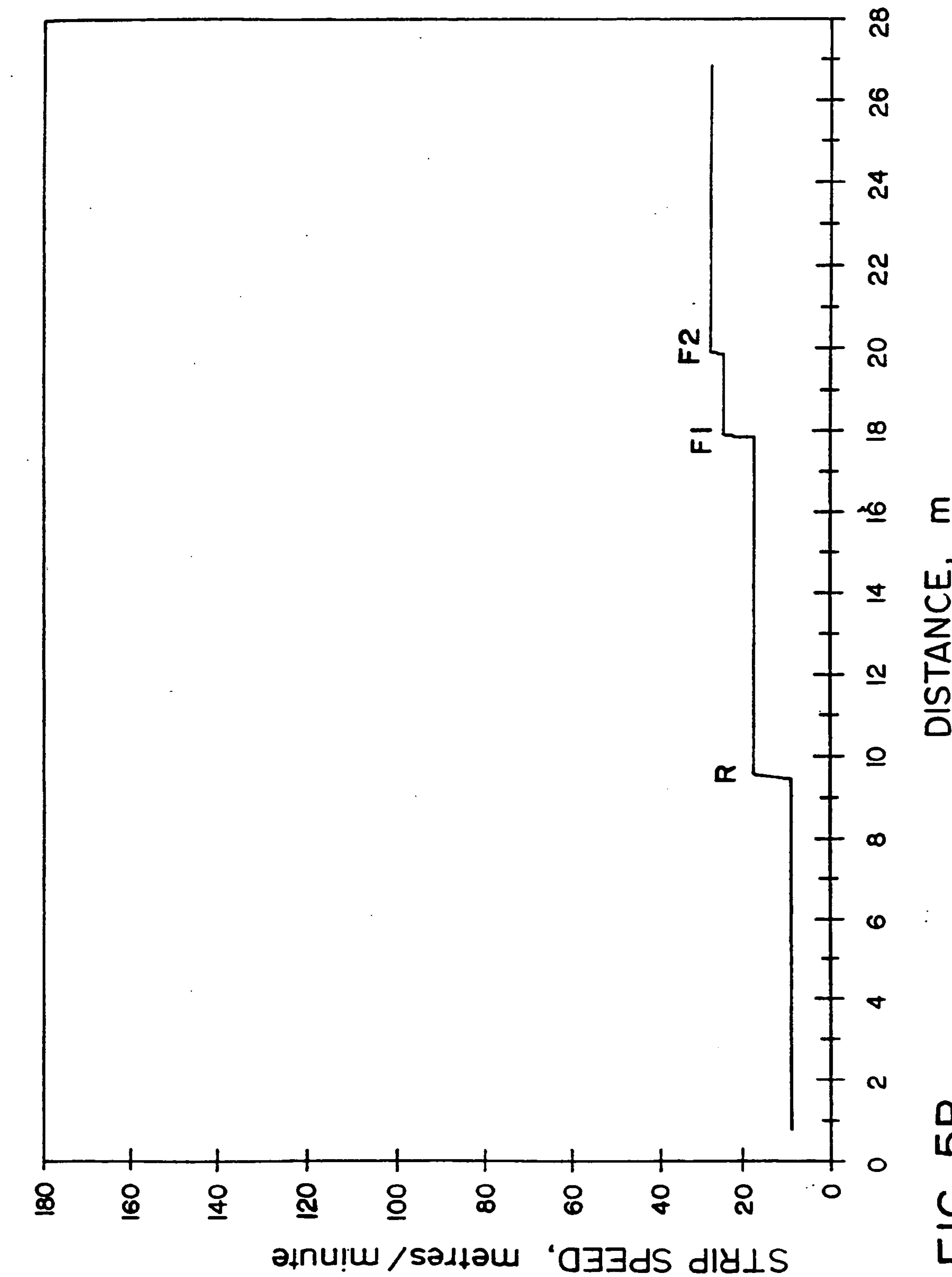

FIG. 5B

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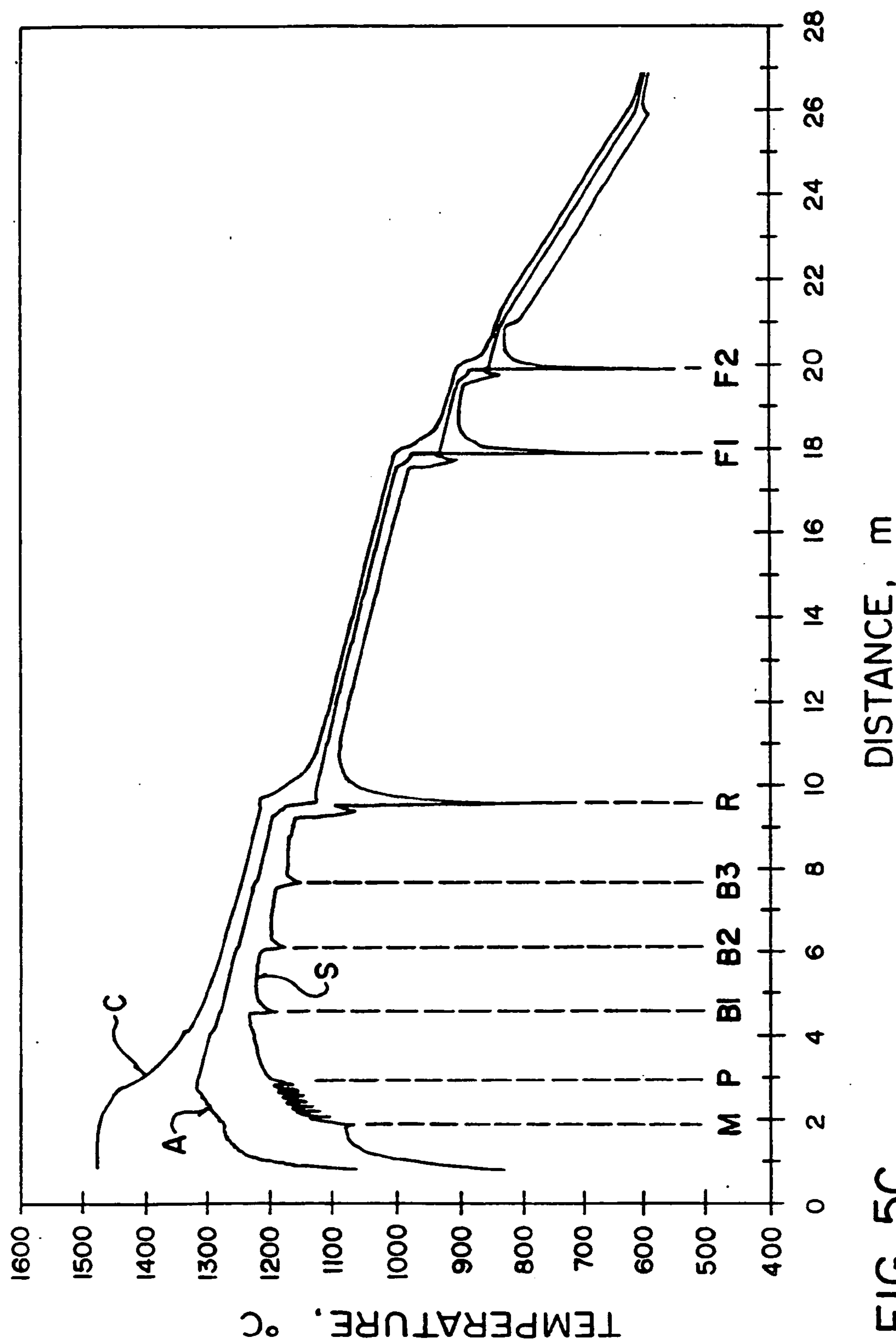
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DISTANCE, m
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2
4
6
8
10
12
14
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28
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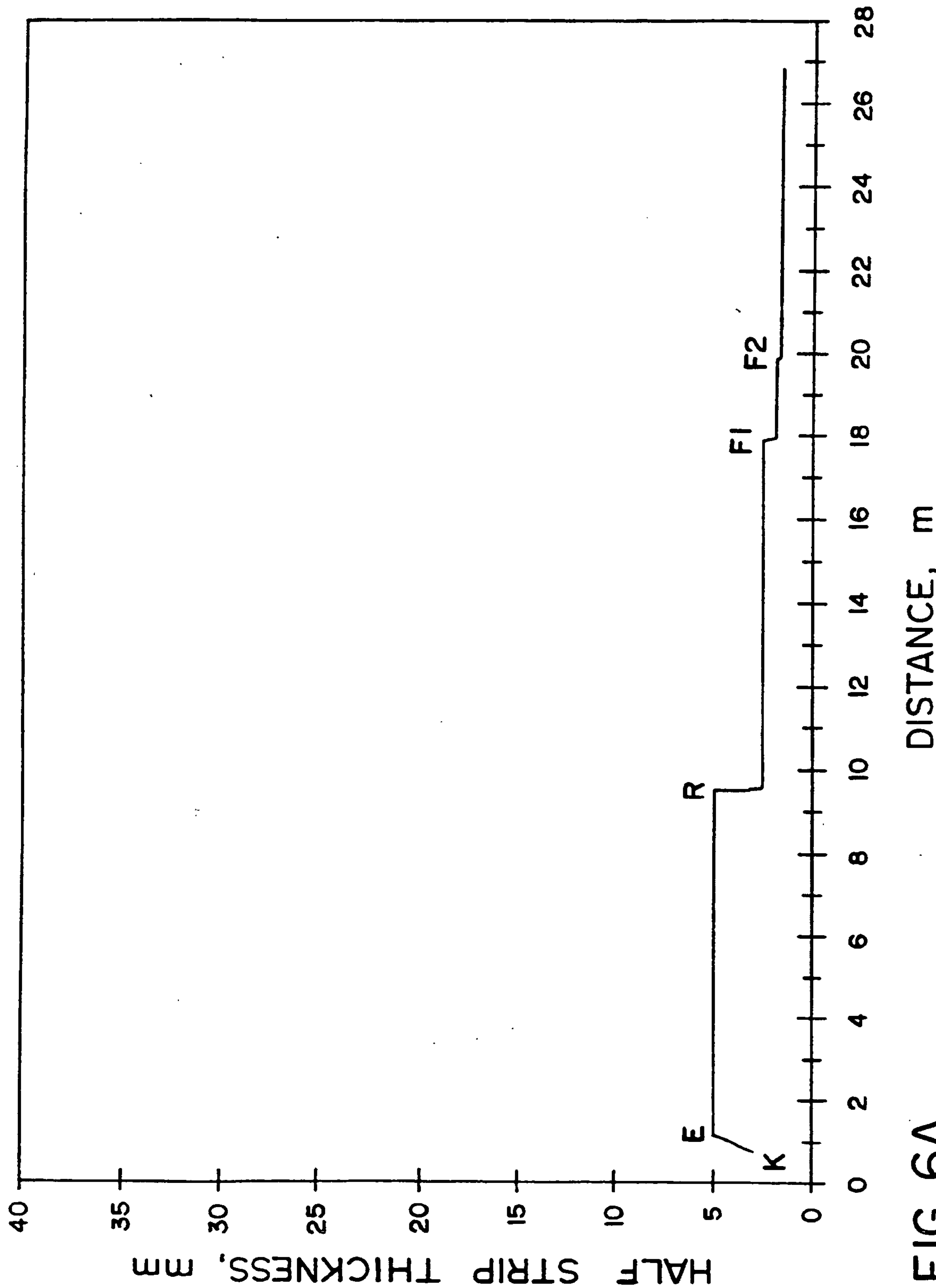
A
S
M
P
BI
B2
B3
R
FI
F2

FIG. 5C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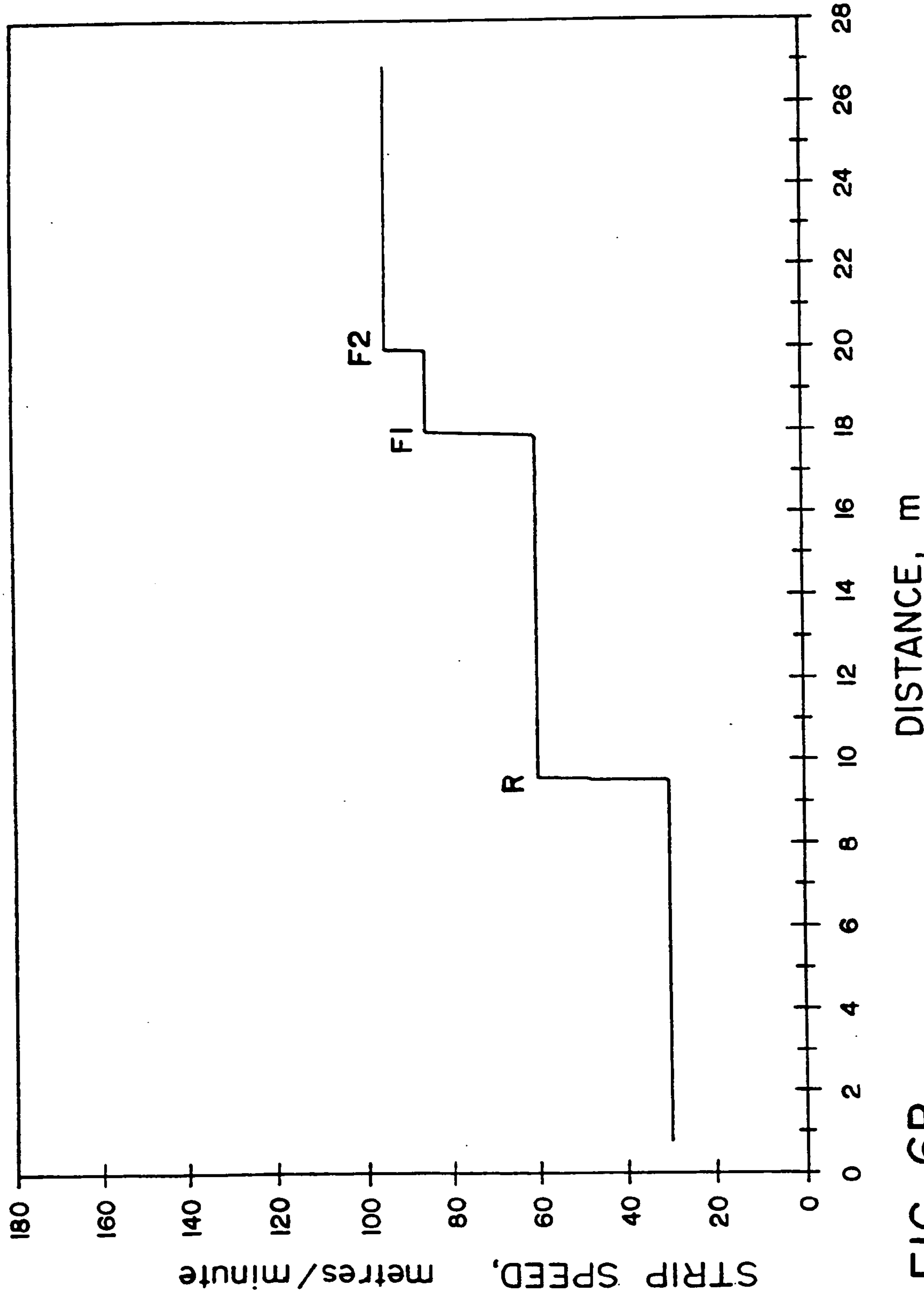
20
22
24
26
28
K
E
R
F1
F2

FIG. 6A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DISTANCE, m
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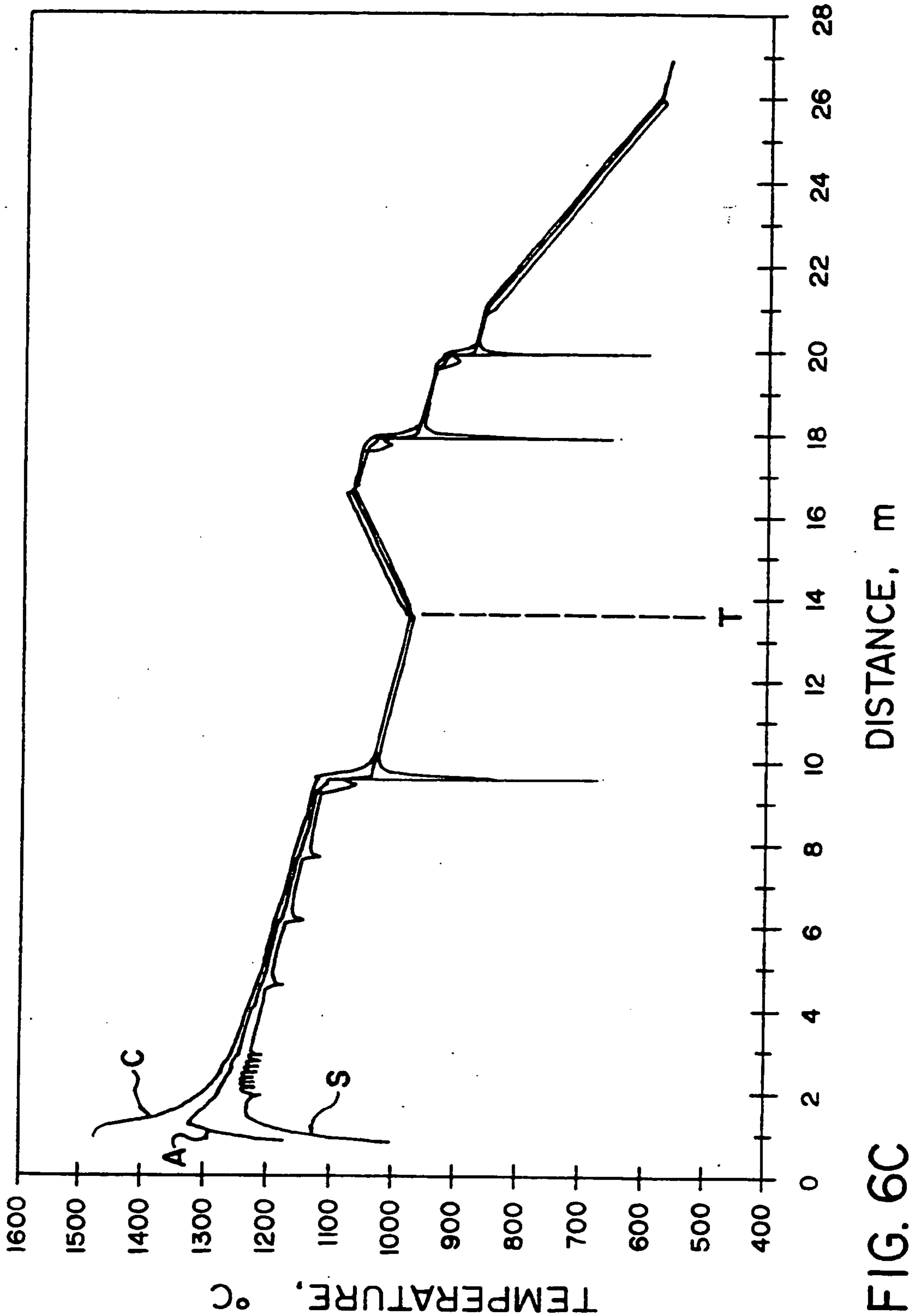
8
10
12
14
16
18
20
22
24
26
28
R
F1
F2

FIG. 6B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DISTANCE, m
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14
16
18
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22
24
26
28
C
A
S
T

FIG. 6C

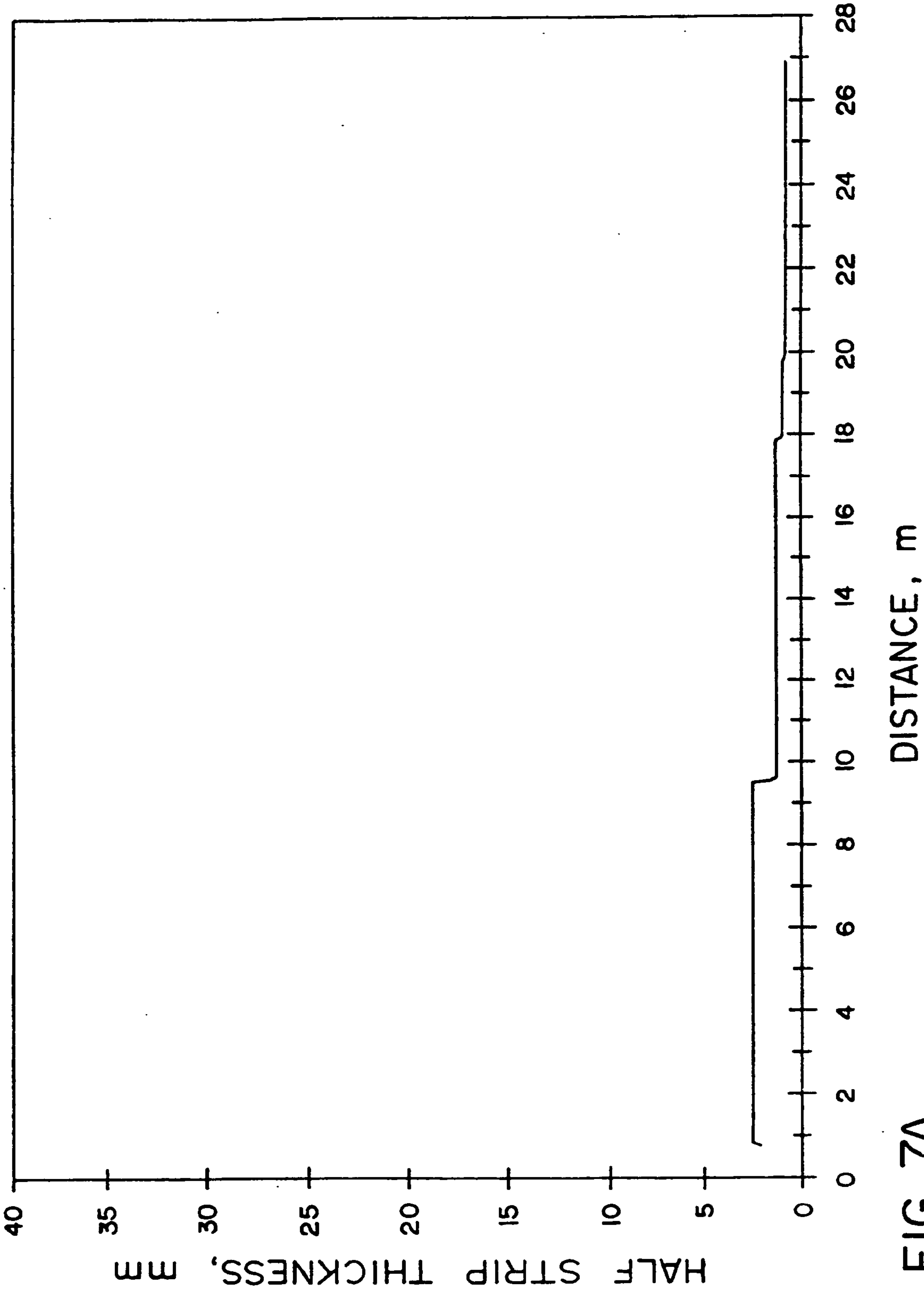

FIG. 7A

11 / 13

SUBSTITUTE SHEET
ISA/EP

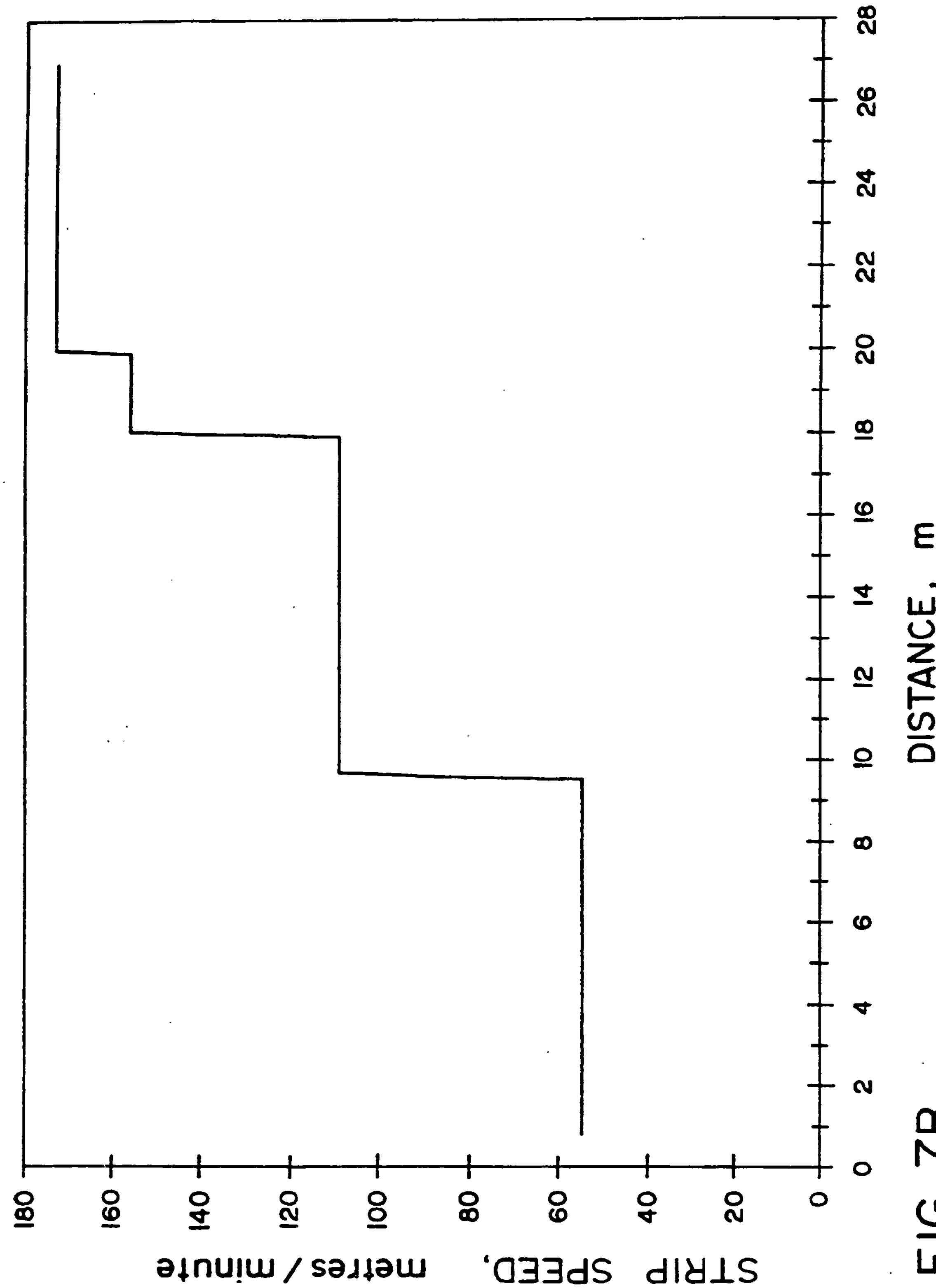
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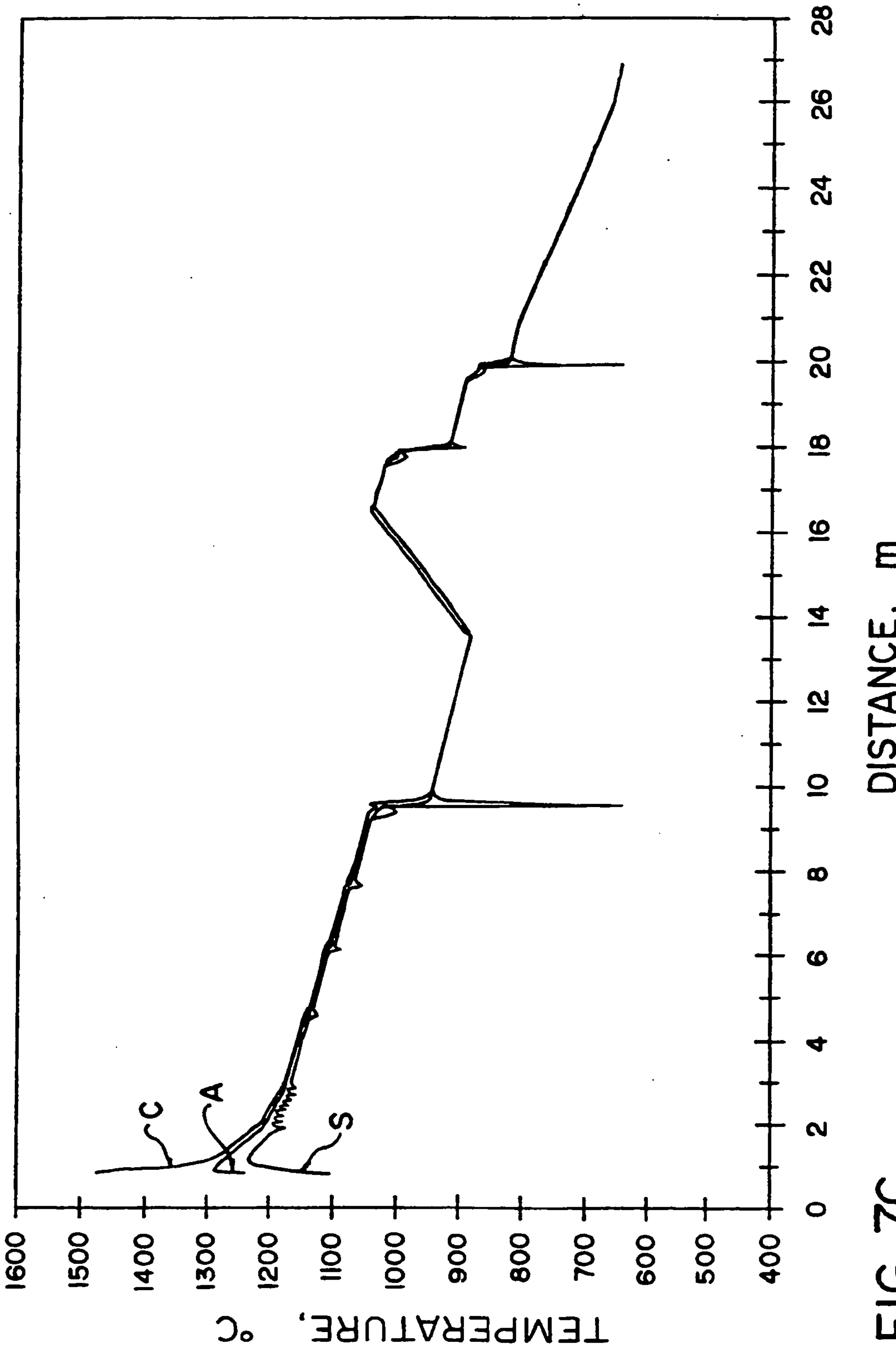
FIG. 7B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A
S

FIG. 7C

INTERNATIONAL SEARCH REPORT

International Application No
PCT/CA 95/00405

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 B22D11/06 B22D11/12

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 B22D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	PATENT ABSTRACTS OF JAPAN vol. 012 no. 045 (M-667) ,10 February 1988 & JP,A,62 197246 (KOBE STEEL LTD) 31 August 1987, see abstract ---	1-5,11
Y	US,A,5 065 811 (SCHOLZ HEINRICH ET AL) 19 November 1991 cited in the application see claims ---	1-5,11
A	PATENT ABSTRACTS OF JAPAN vol. 015 no. 267 (M-1133) ,8 July 1991 & JP,A,03 090261 (NIPPON STEEL CORP) 16 April 1991, cited in the application see abstract --- -/--	1,11

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
23 October 1995	05.12.95
Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax (+31-70) 340-3016	Authorized officer WOUDENBERG, S

International Application No
PCT/CA 95/00405

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	PATENT ABSTRACTS OF JAPAN vol. 011 no. 278 (M-623) ,9 September 1987 & JP,A,62 077151 (NIPPON STEEL CORP) 9 April 1987, cited in the application see abstract -----	31,32

INTERNATIONAL SEARCH REPORT

Internal Application No
PCT/CA 95/00405

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
US-A-5065811	19-11-91	DE-A-	3839954	31-05-90
		EP-A,B	0371281	06-06-90
		JP-A-	2197358	03-08-90